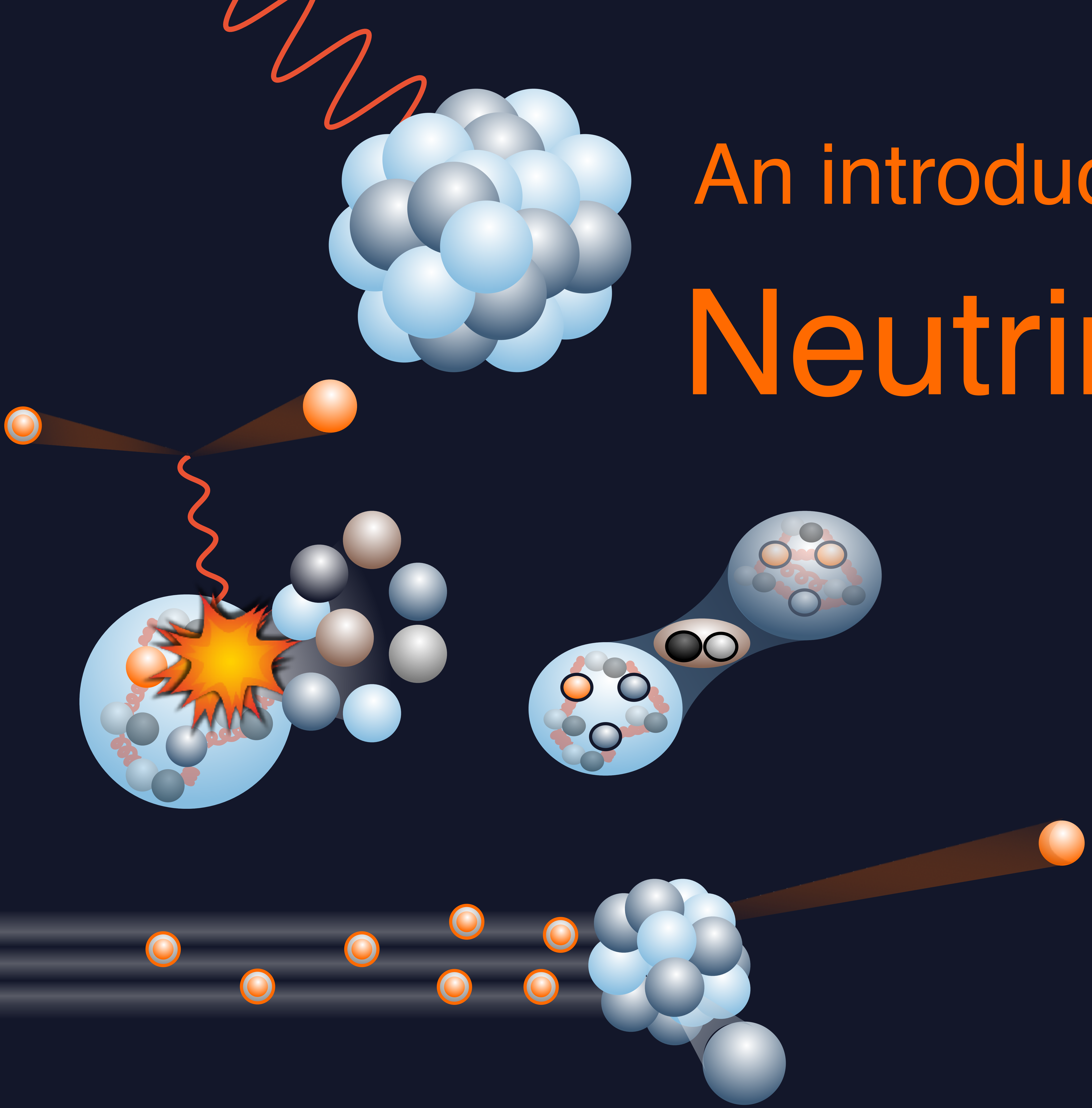


An introduction to

Neutrino-Interaction Physics

Cheryl Patrick

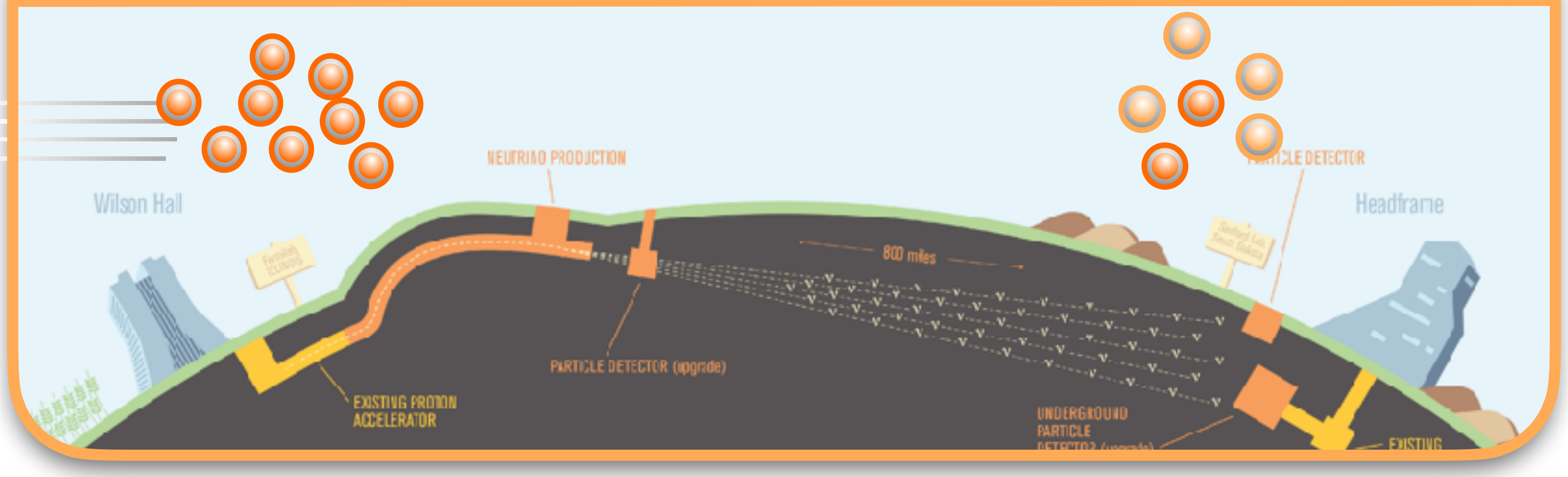
University College London

June 7th, 2021

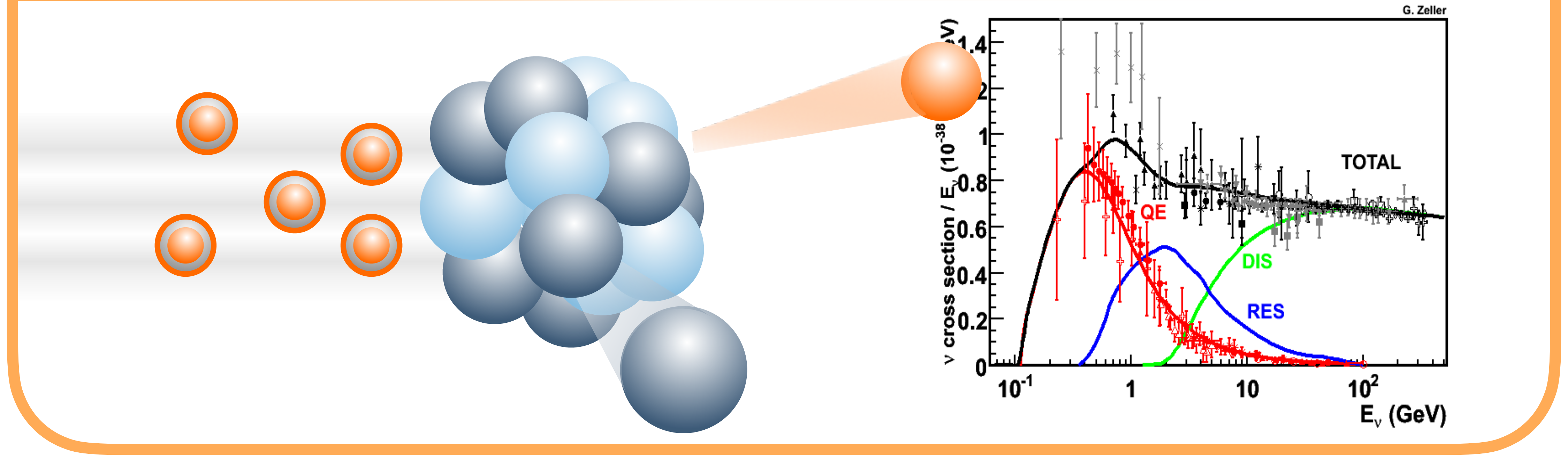
Neutrino
Interaction
School 2021

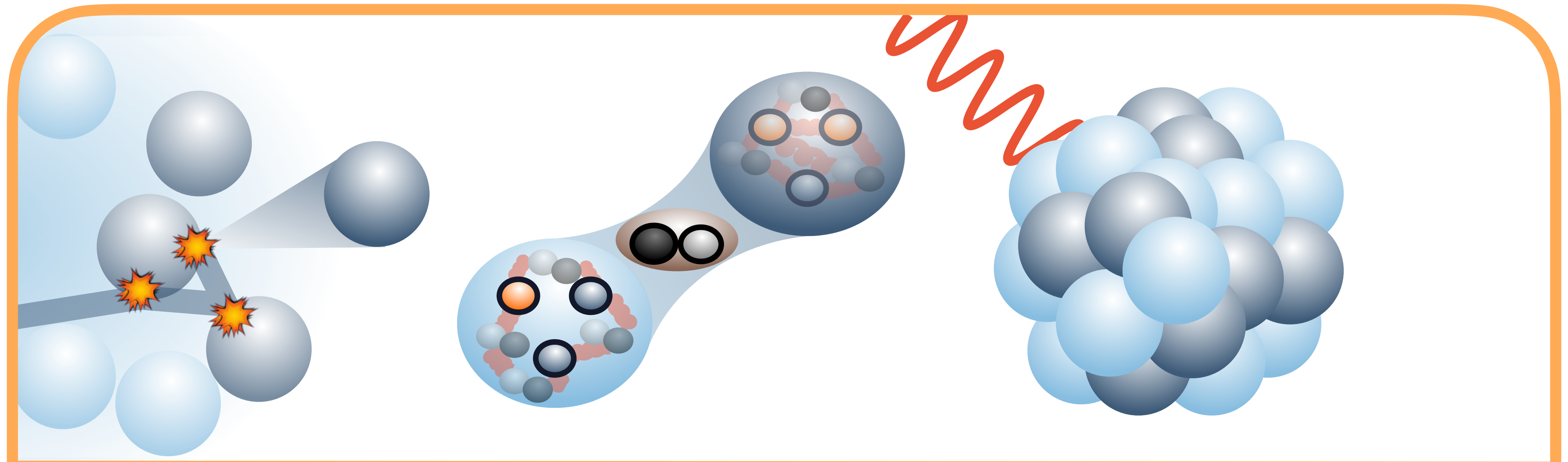
Neutrino interactions and…

Why they’re so important

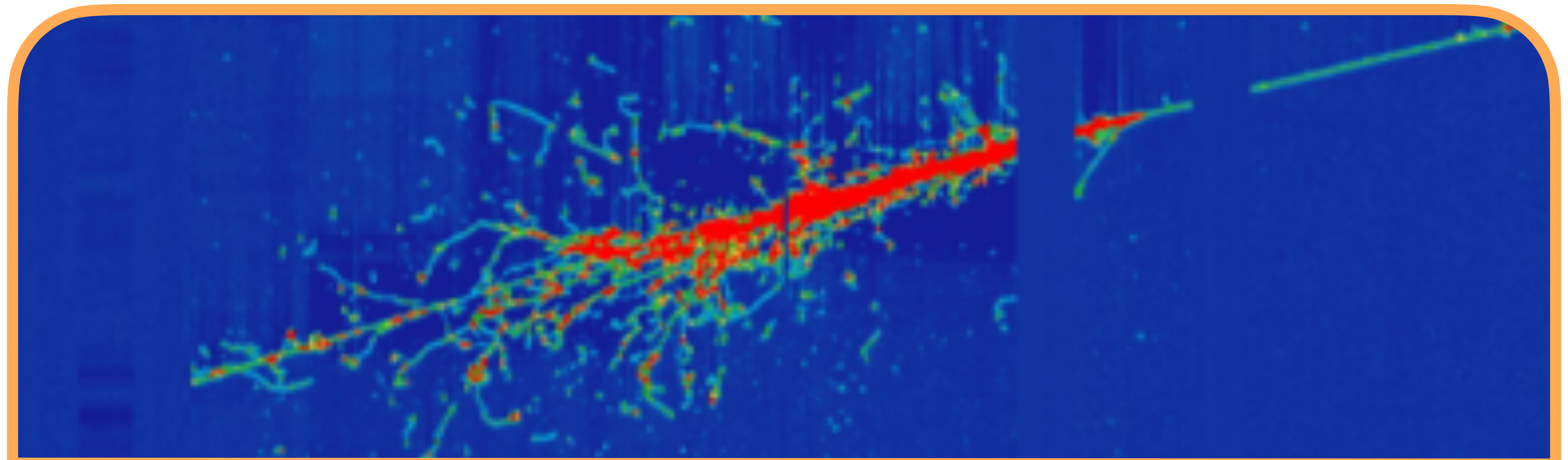


What we know about them





What we still need to understand better



How we’re trying to understand them

Warm-up puzzle - meet the cast!

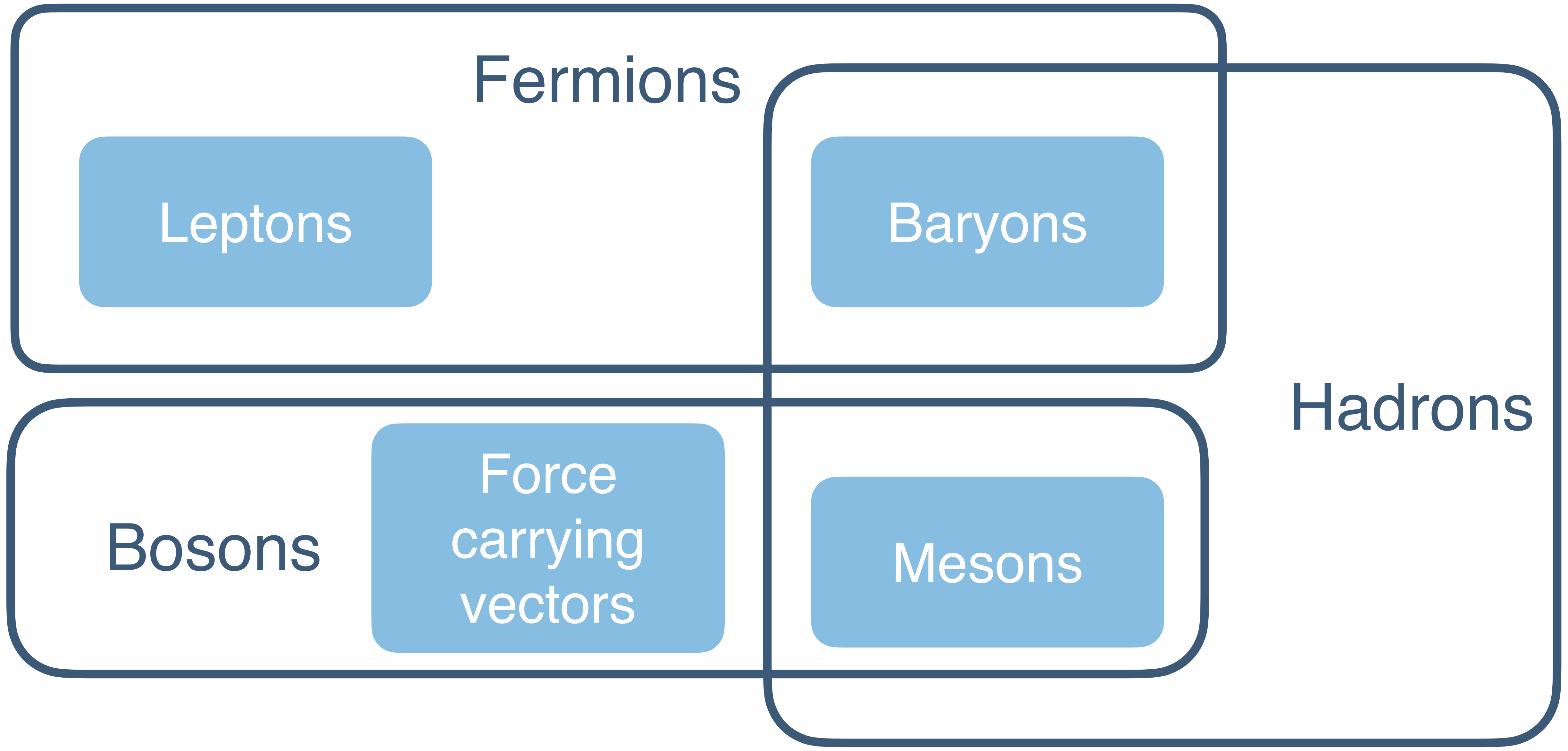
Exercise 1

What are these particles'…?

Charges

Spins

Which particles are…?



Fermions

Leptons

Baryons

Hadrons

Bosons

Force carrying vectors

Mesons

Muon-neutrino, ν_μ

Electron-neutrino, ν_e

Electron, e^-

Muon, μ

Proton, p

Neutron, n

Pion, π (3 of them)

Photon, γ

Positron, e^+

Weak force carrier, W (2 of them)

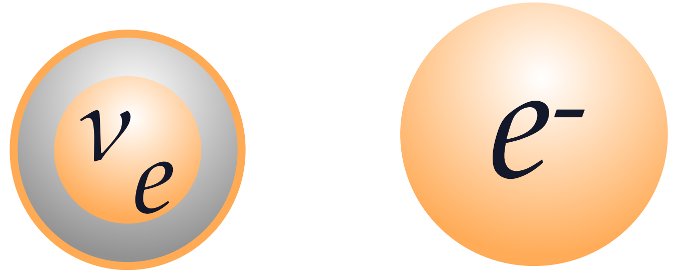
Weak force carrier, Z

Δ-1232 resonance (4 of them)

Can you match the particles to the categories?

Neutrinos (Three different ones)

Electron flavor

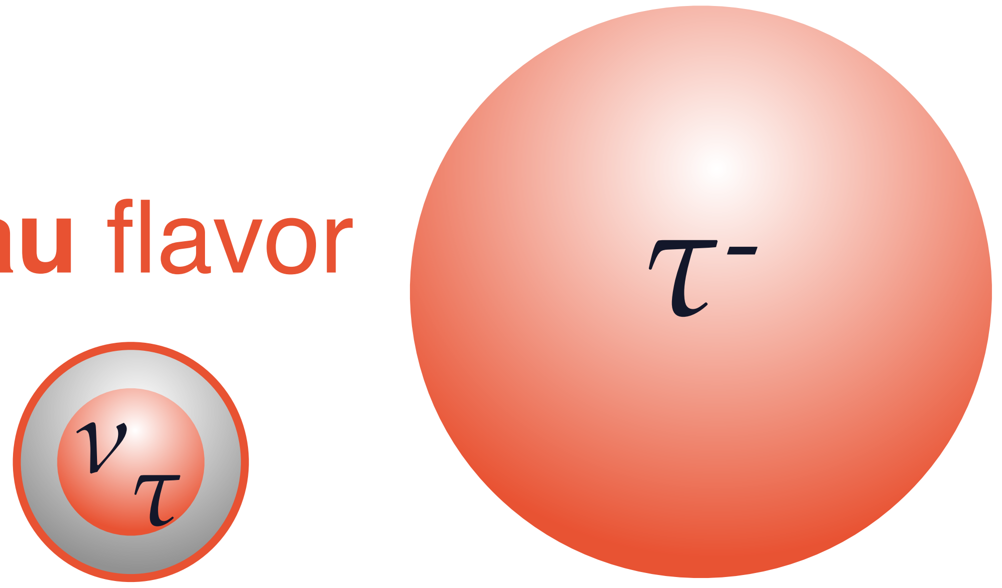


m_e= 511 keV

Muon flavor

m_μ= 106 MeV

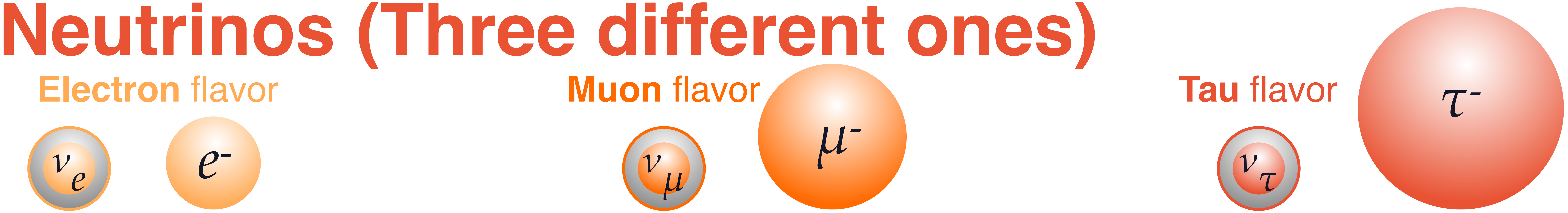
Tau flavor



m_τ= 1.8 GeV

- **No electric charge**
- **Leptons** (fermions, spin 1/2). Always **left-handed** (antineutrinos always right-handed)
- Massless (in the Standard Model)
- Interact via **weak interaction** only…

Neutrinos (Three different ones)



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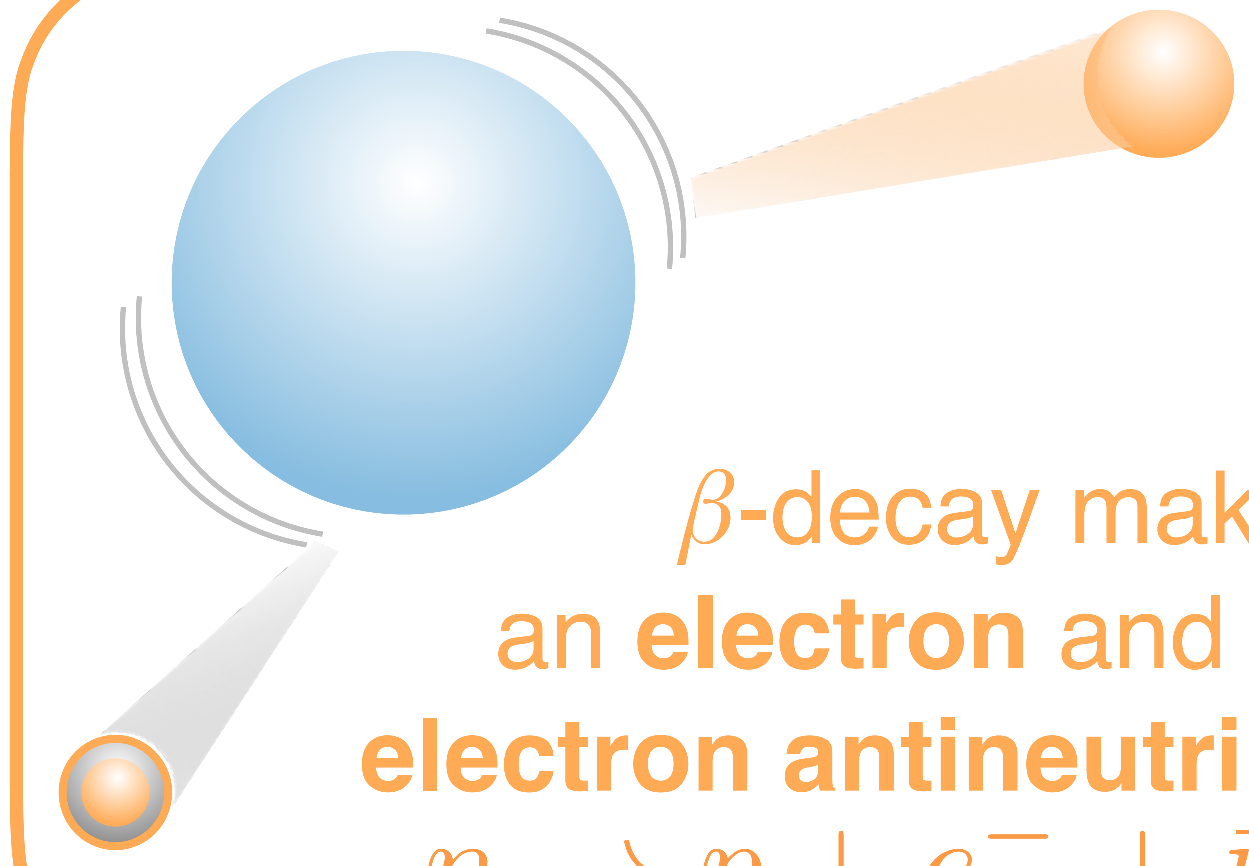
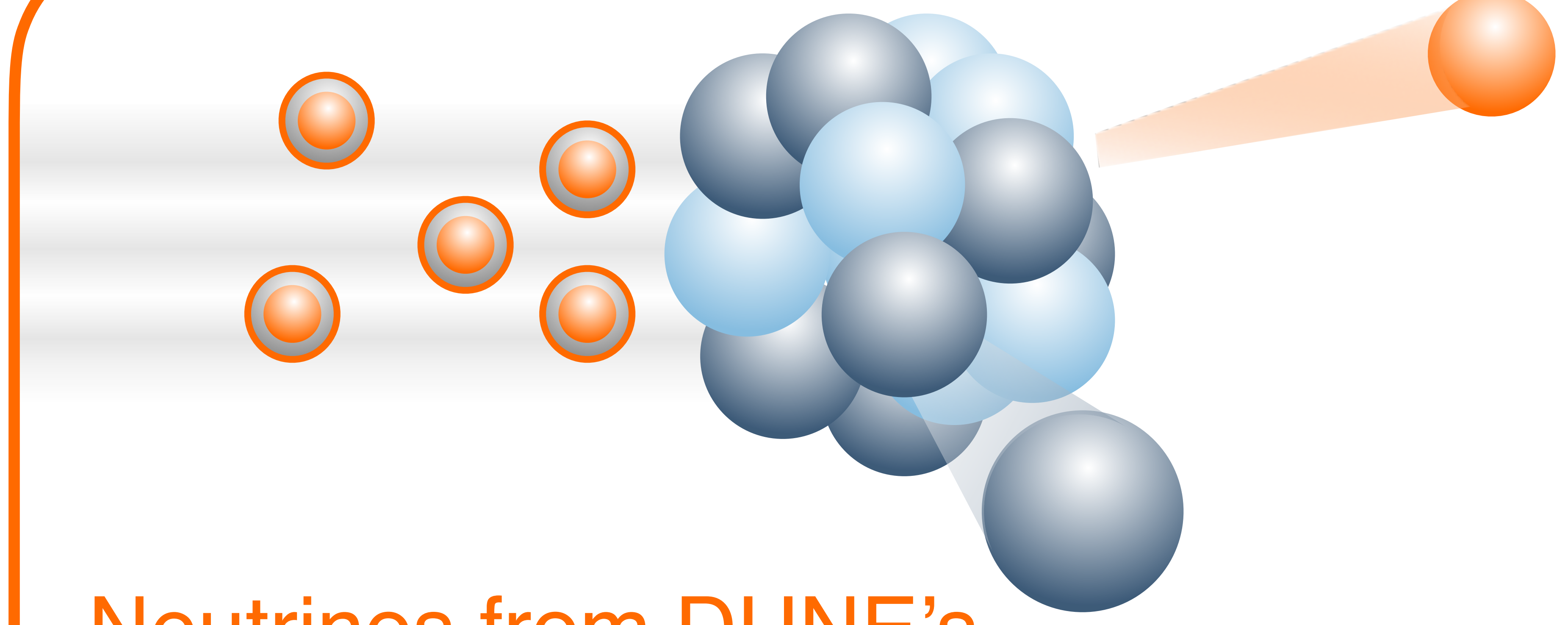


β-decay makes an **electron** and an **electron antineutrino**

$$n \rightarrow p + e^- + \bar{\nu}_e$$



Neutrinos from DUNE's (mostly) ν_μ beam interact to make **muons**

Neutrinos (Three different ones)

Electron flavor

ν_e e^-

m_e= 511 keV

Muon flavor

ν_μ μ^-

m_μ= 106 MeV

Tau flavor

ν_τ τ^-

m_τ= 1.8 GeV

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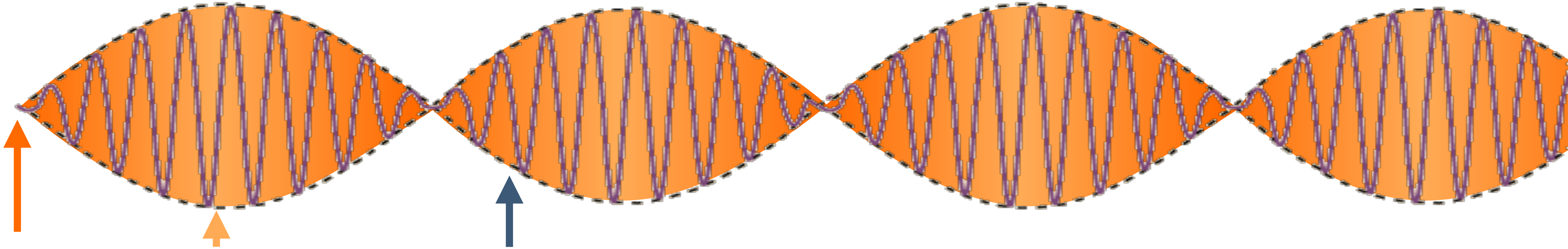
- **Oscillate** between flavors over time…
- … and therefore have **mass** (massless particles don't see time)



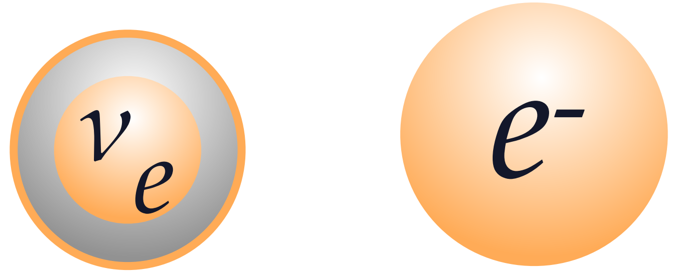
ν_μ here

ν_e here

Could be either here

Neutrinos (Three different ones)

Electron flavor



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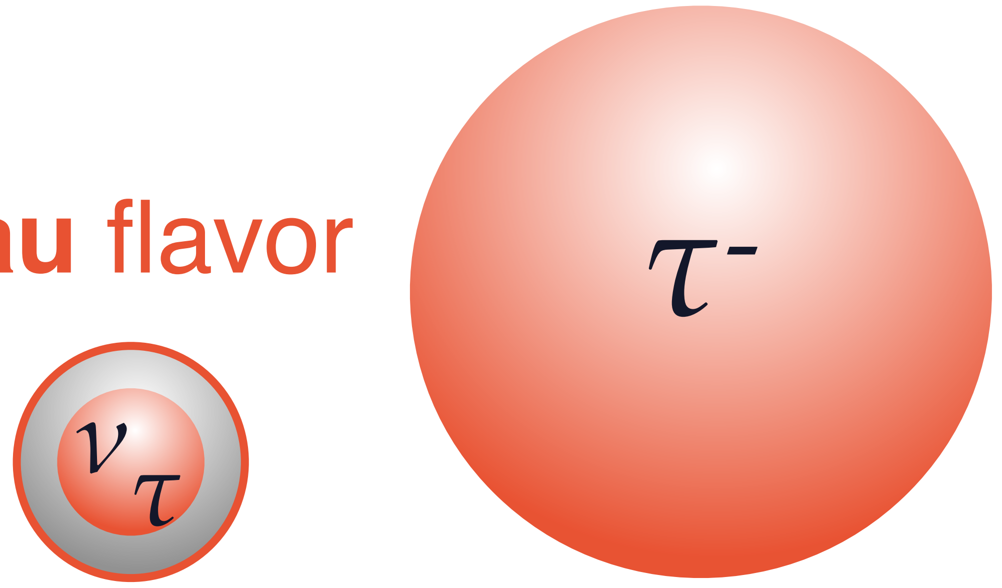

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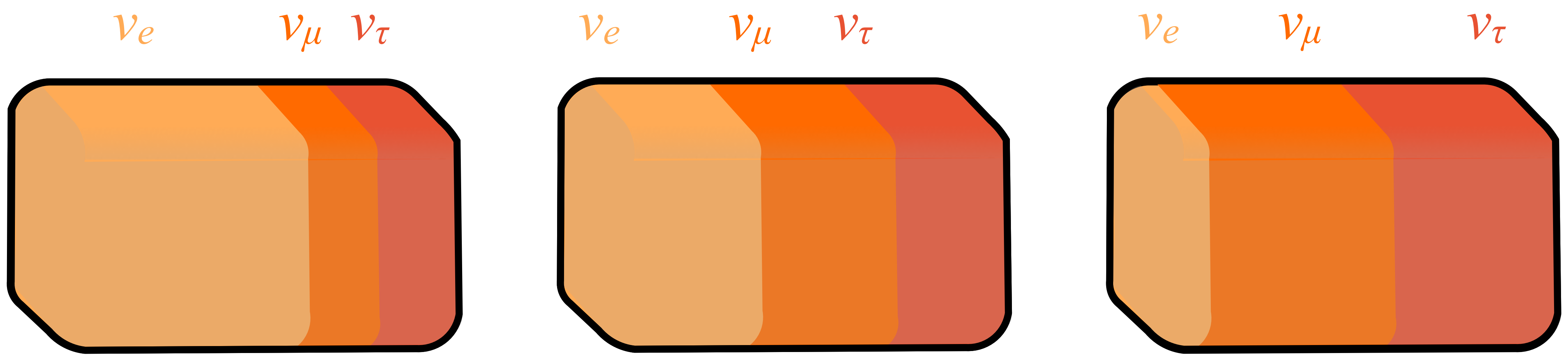
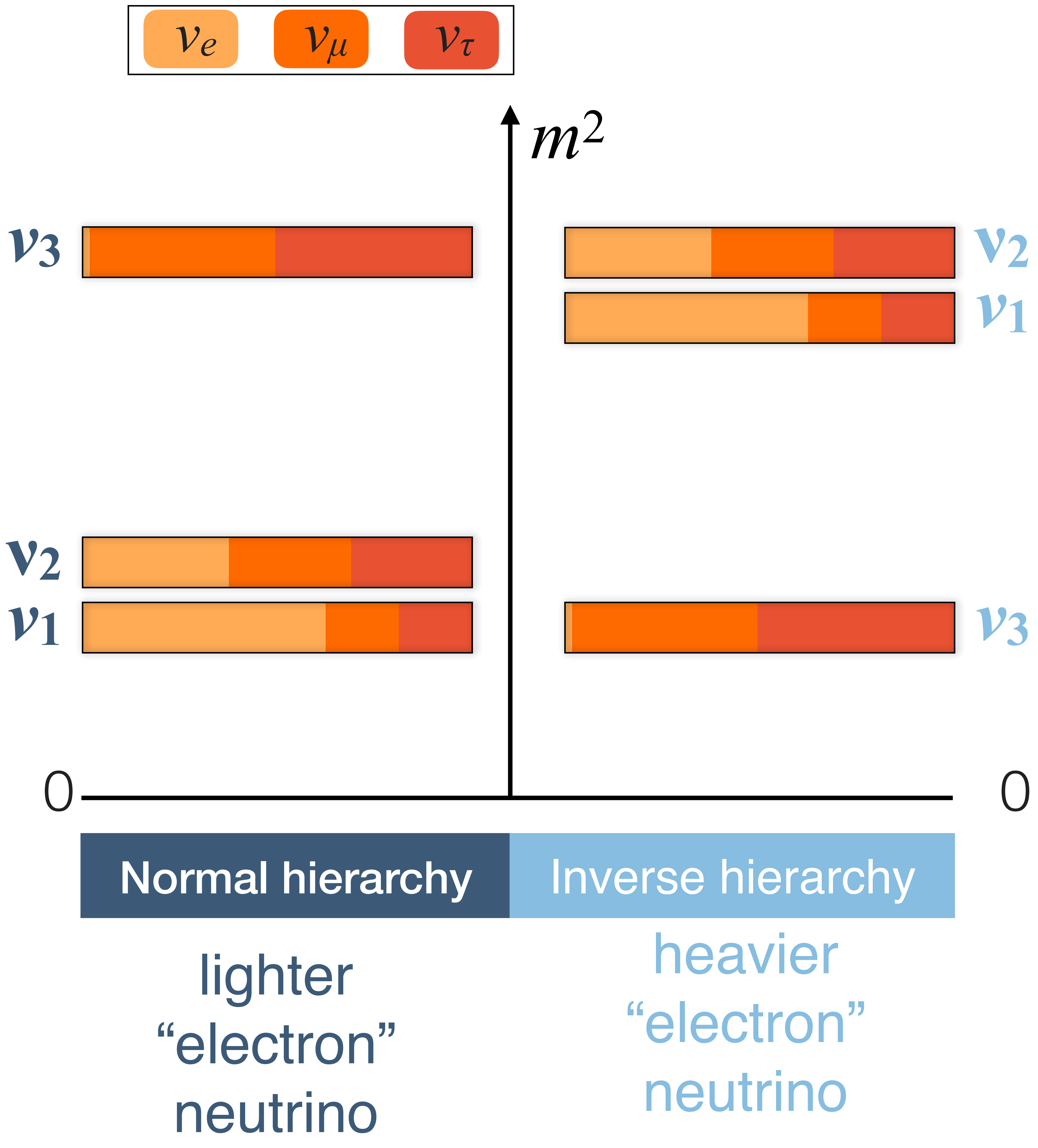
- Interact via **weak interaction** only… which conserves **lepton flavor**
- **Oscillate** between flavors over time…
- … and therefore have **mass** (massless particles don't see time)
- The three mass states are a **mix** (quantum superposition) of flavor states



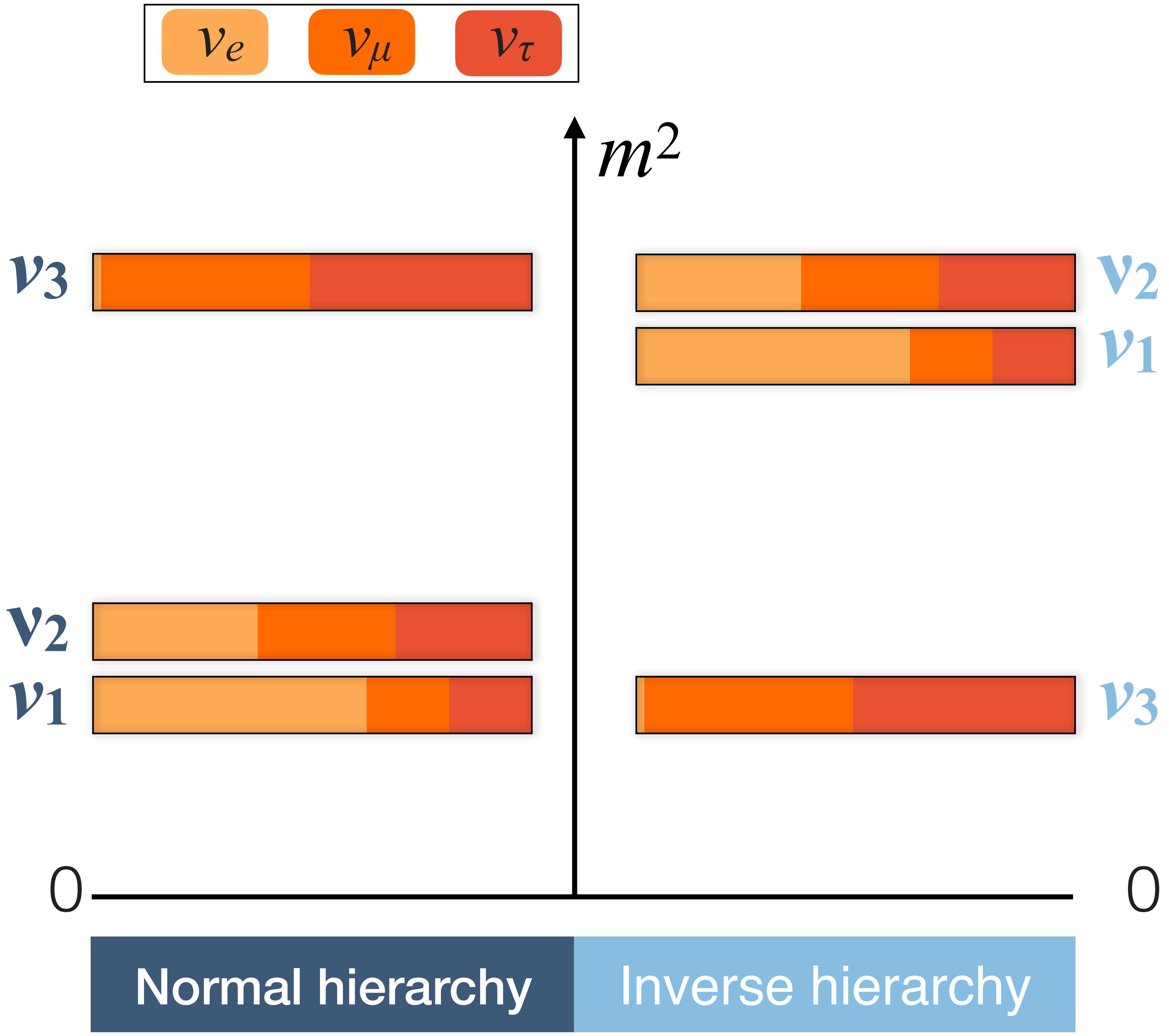
Mass state ν_1 **Mass state** ν_2 **Mass state** ν_3

Big questions of neutrino physics



Which neutrino is lightest?

Big questions of neutrino physics



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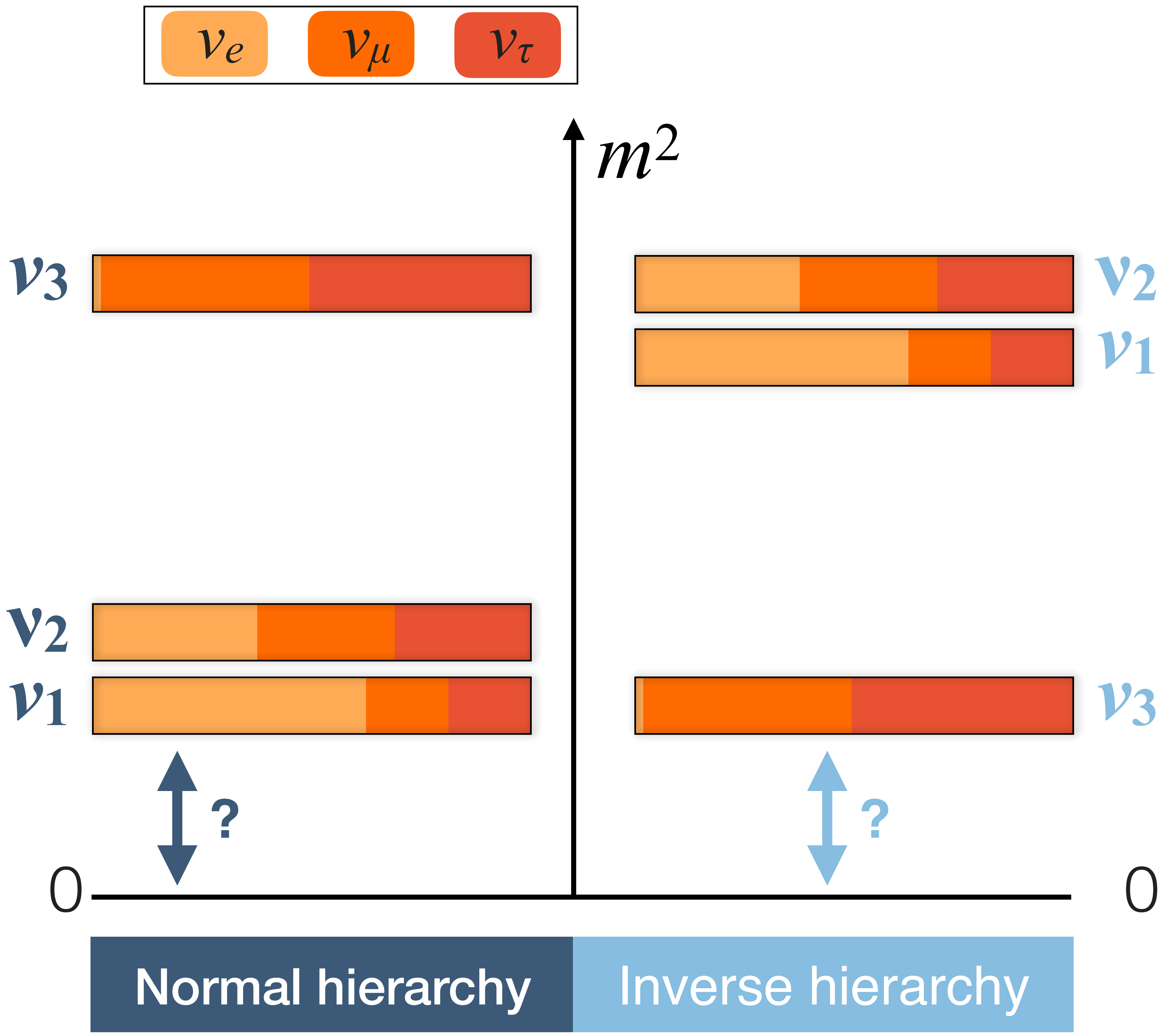
Charge-parity (CP) violation:
Do ν and $\bar{\nu}$ behave the same?

Big questions of neutrino physics



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What's the absolute mass scale?

How do neutrinos get their mass?

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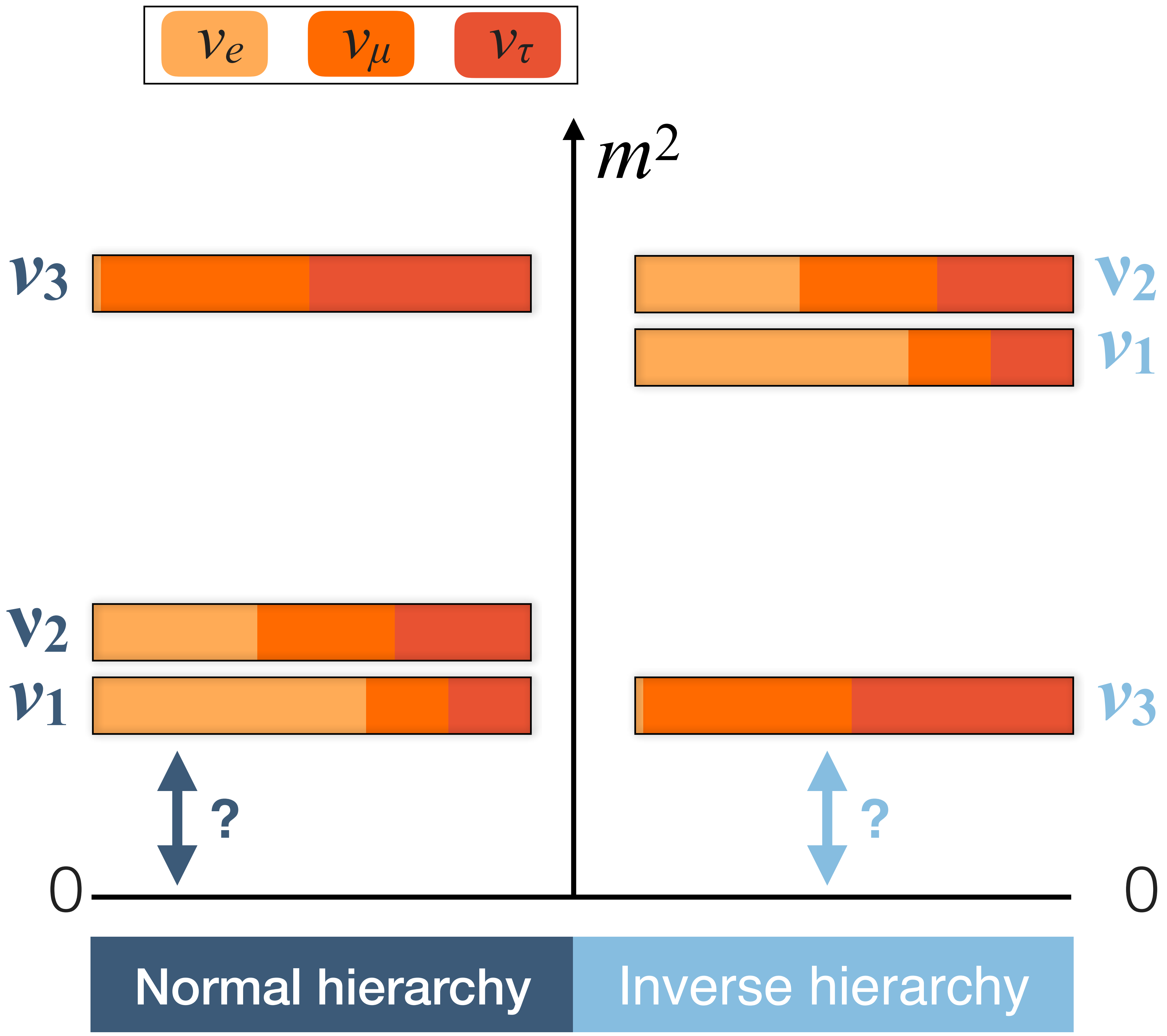

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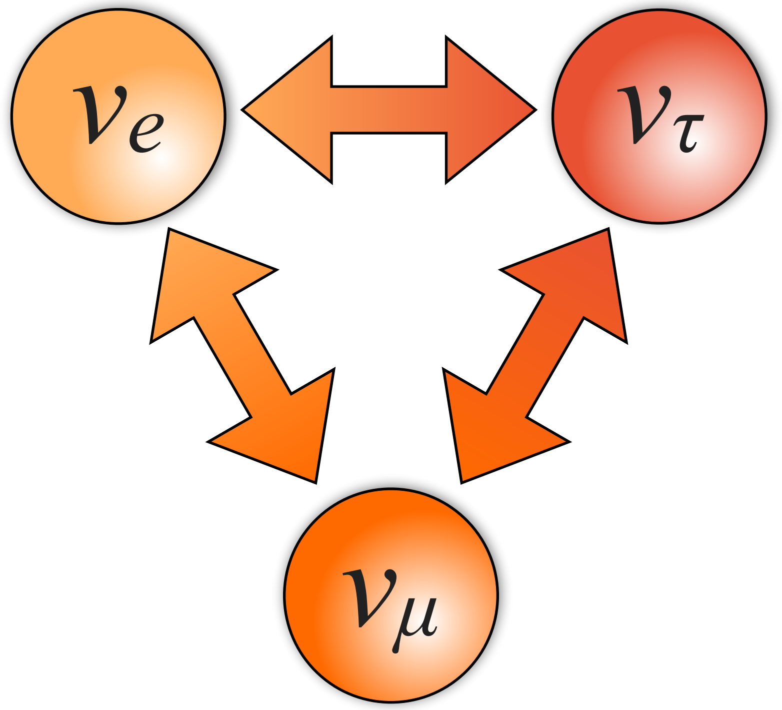

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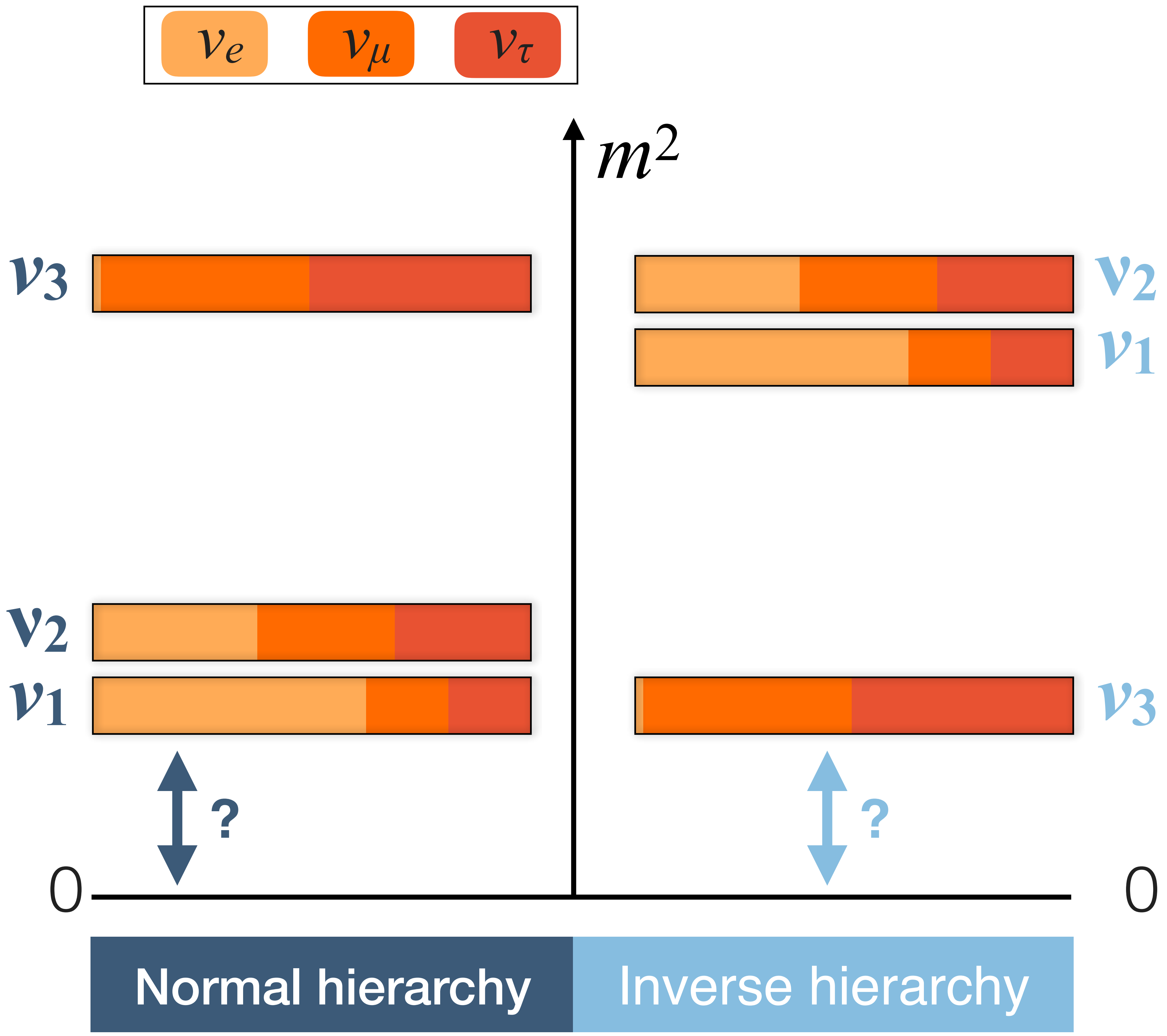

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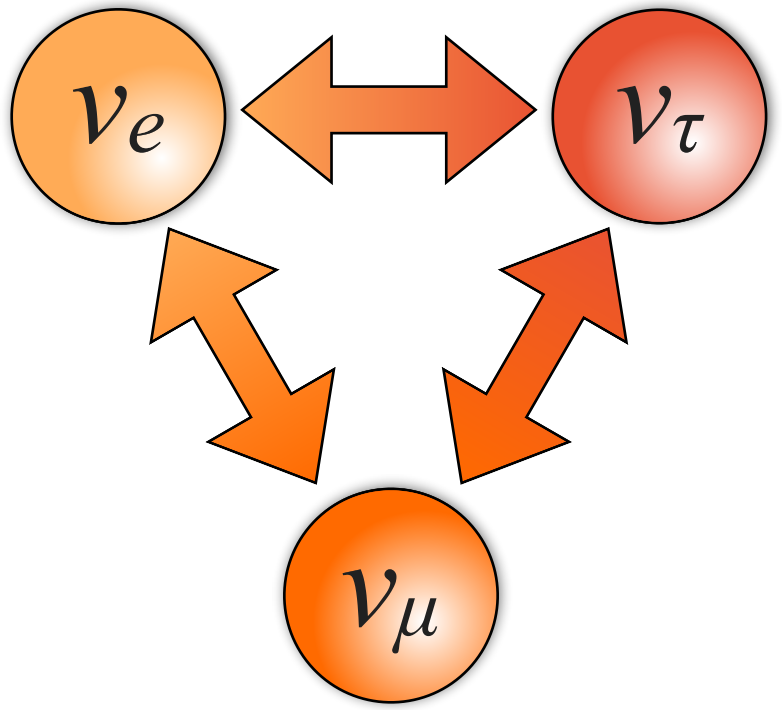

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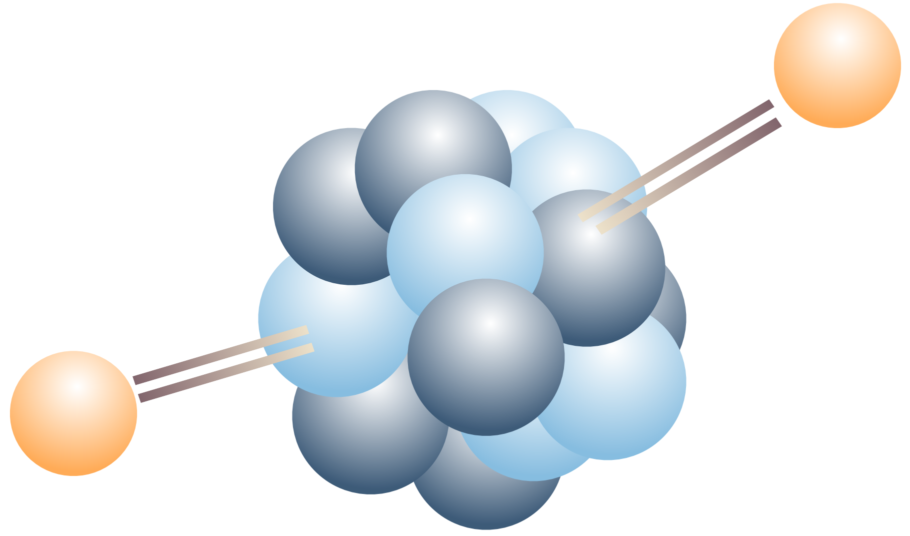
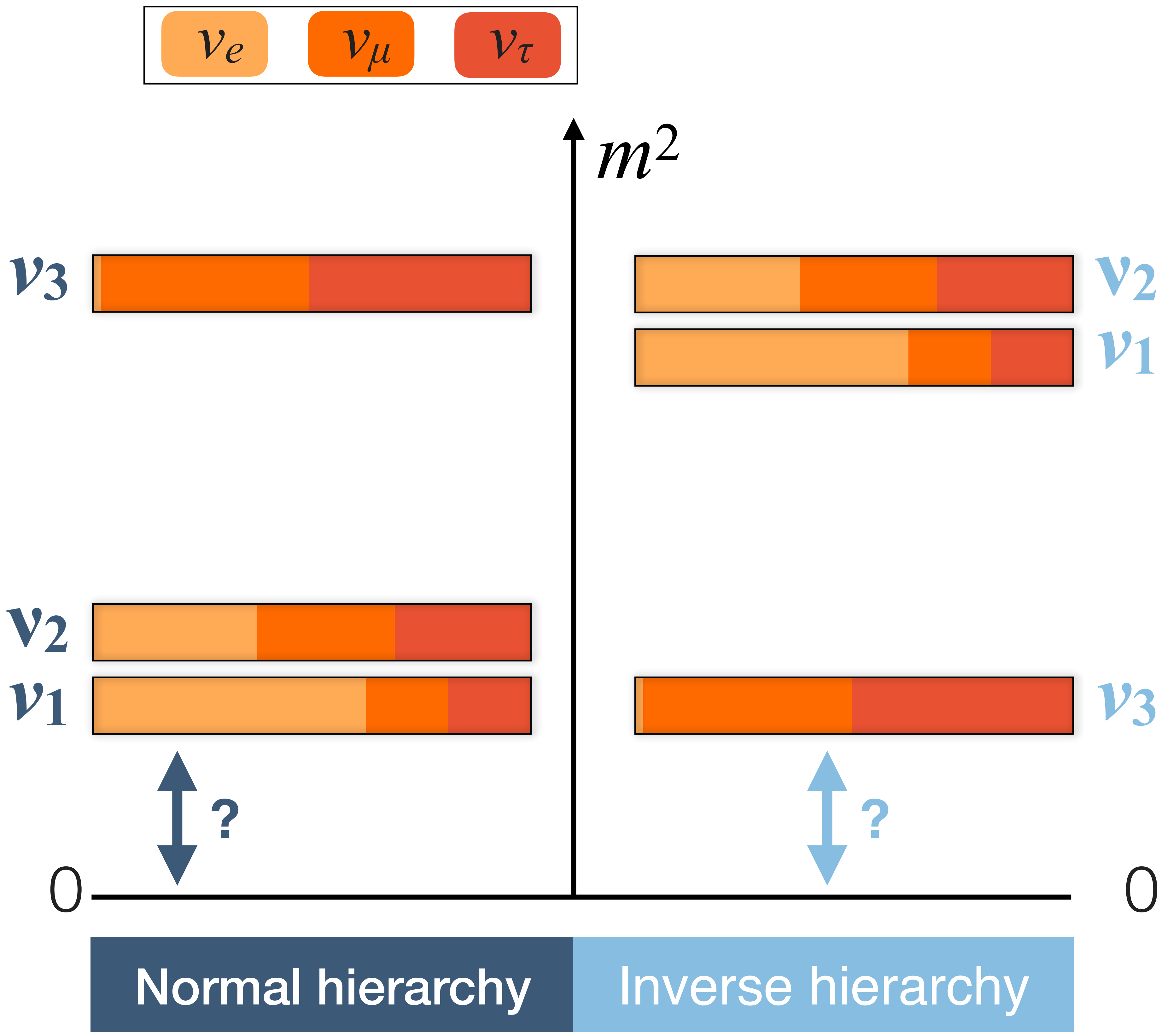


Neutrinoless double-beta decay, direct mass searches

Big questions of neutrino physics



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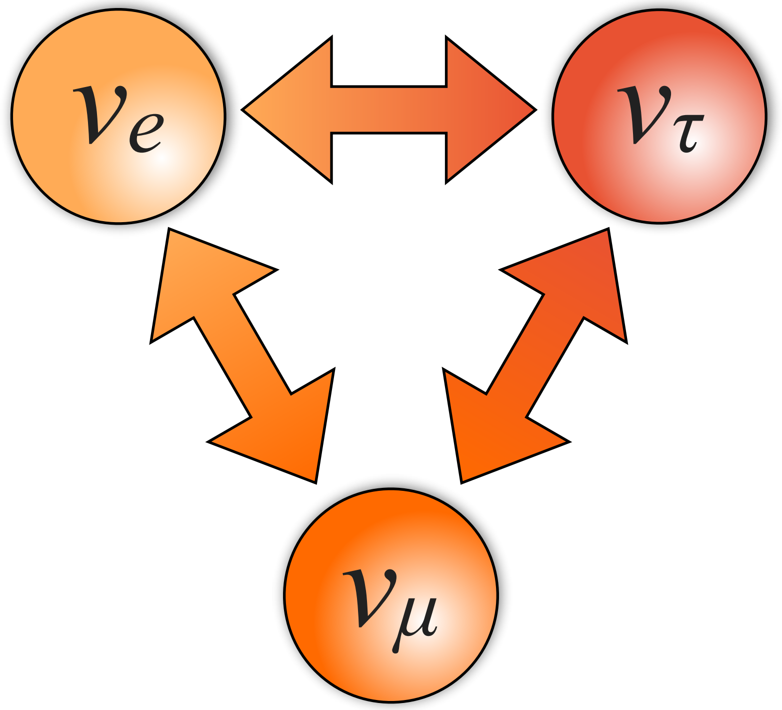

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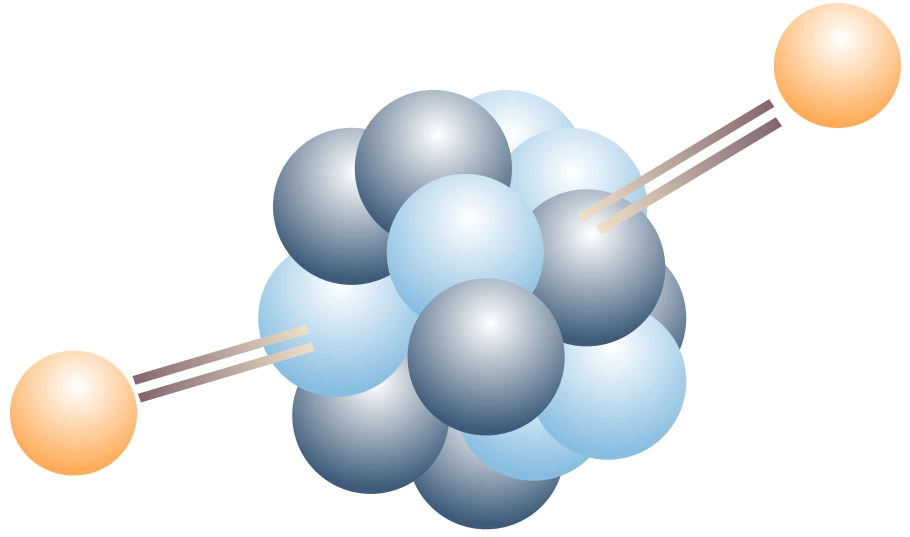


Neutrinoless double-beta decay, direct mass searches

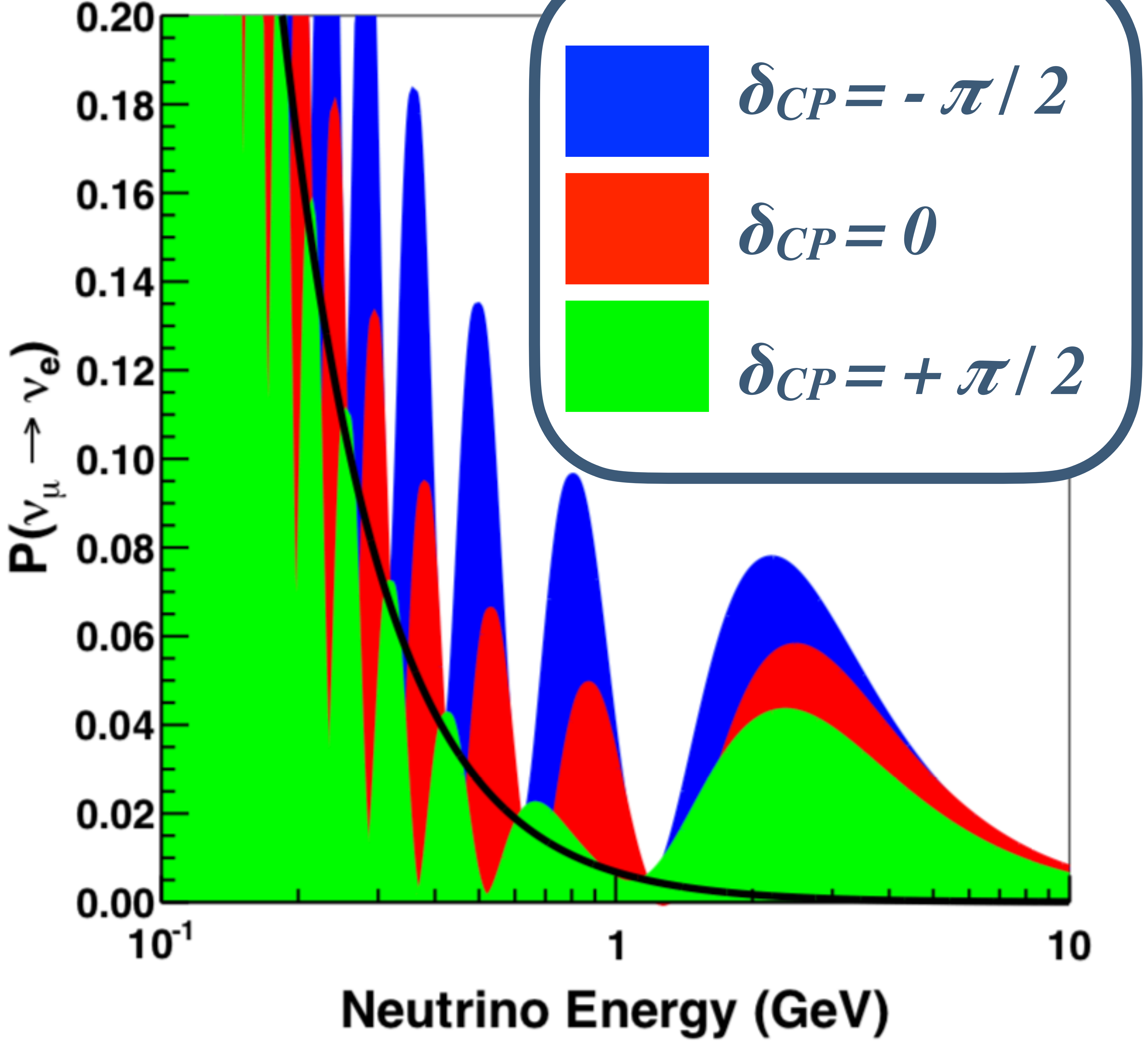
Cosmology

What's DUNE looking for?

Charge-parity violation

The CP-violating parameter δ_{CP} alters this probability distribution:

arXiv:2002.03005 [hep-ex]



What's DUNE looking for?

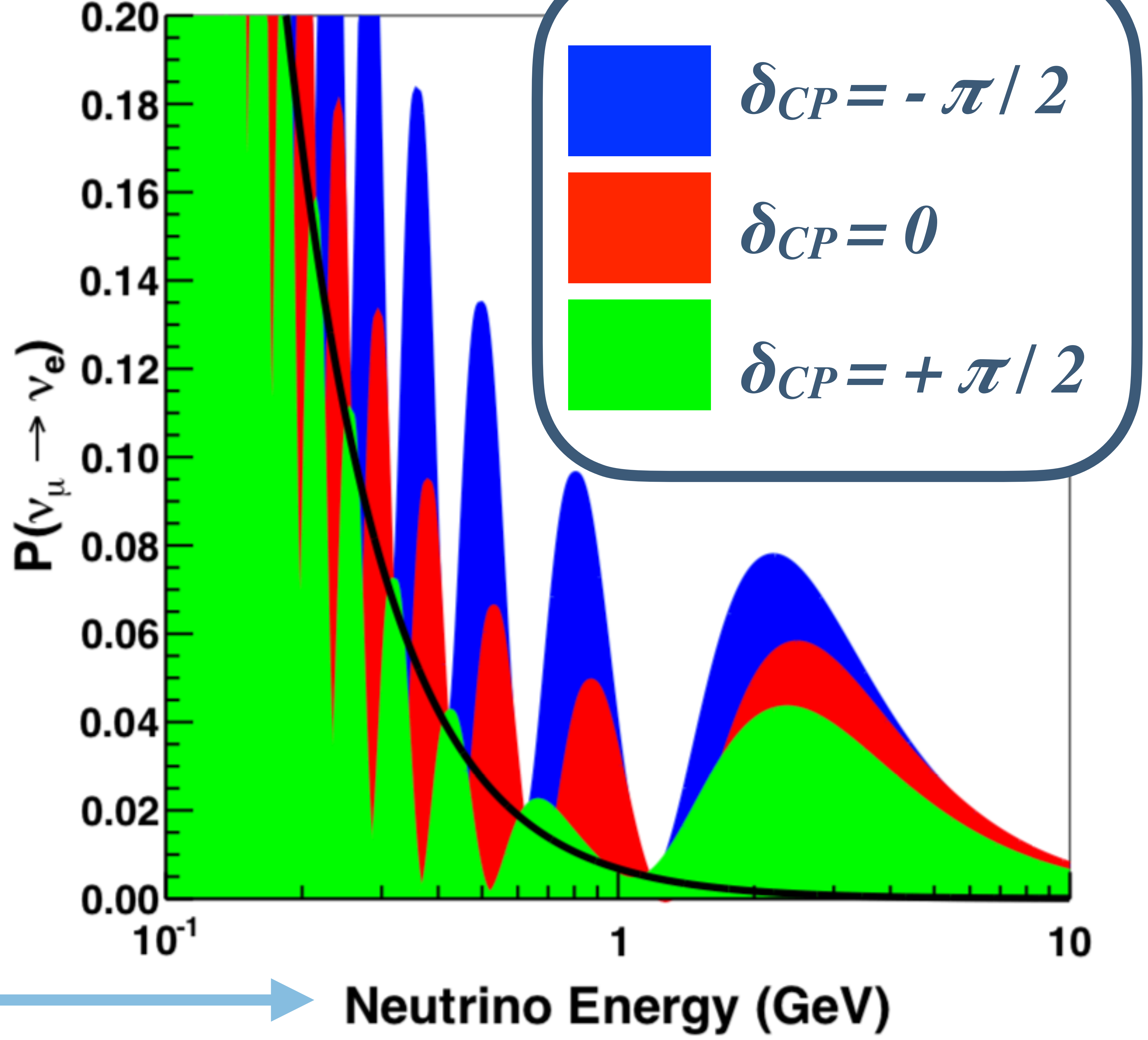
Charge-parity violation

The CP-violating parameter δ_{CP} alters this probability distribution:

Fraction of ν_μ that have oscillated into ν_e

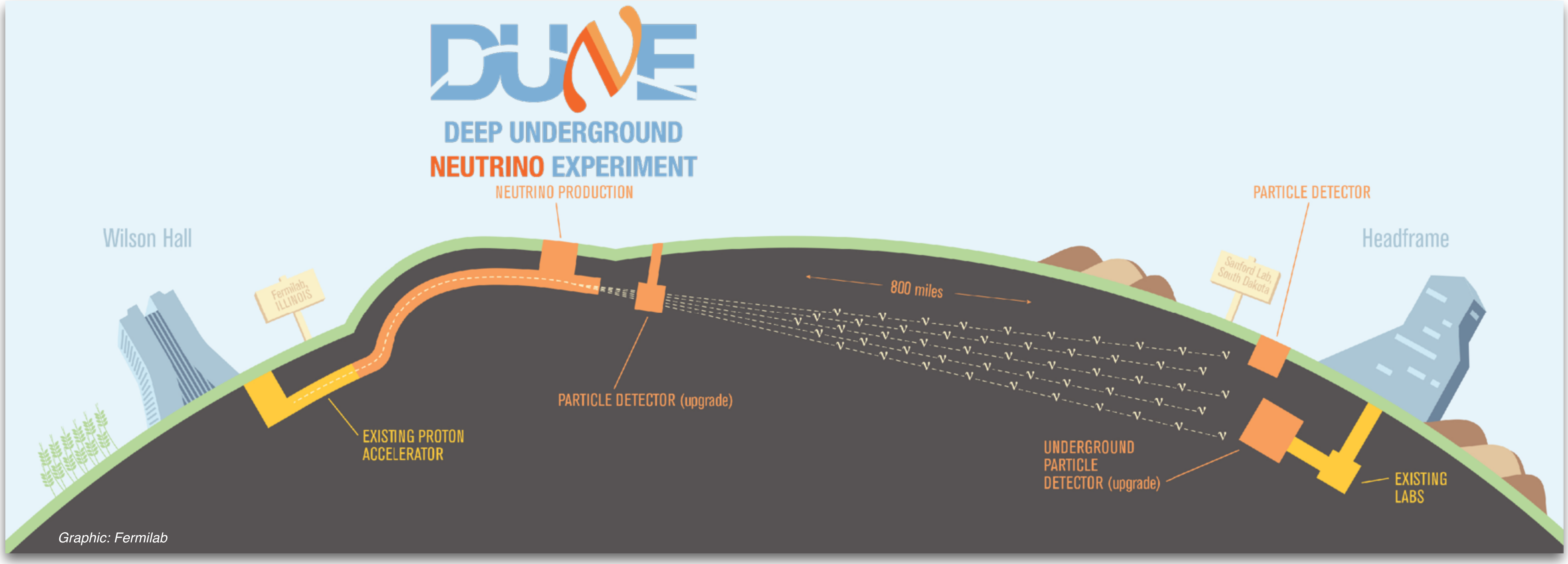
as a function of

Neutrino energy



arXiv:2002.03005 **[hep-ex]**

Here’s how it will do it:



Graphic: Fermilab

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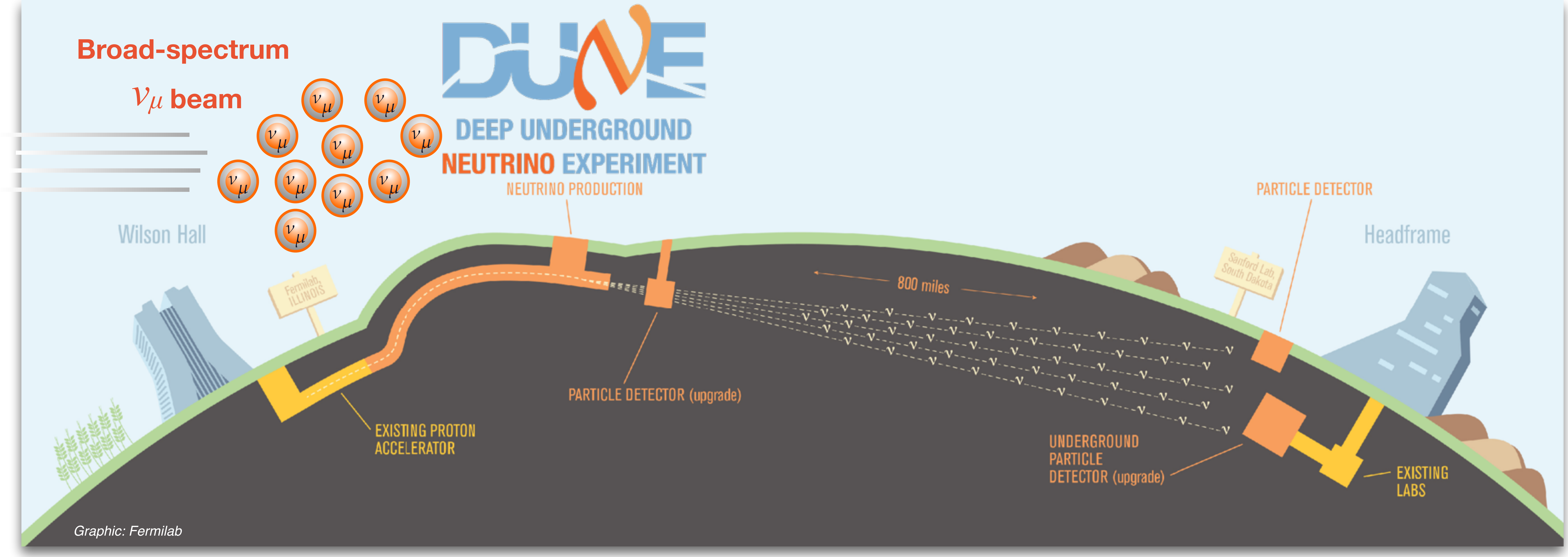

Graphic: Fermilab

How many neutrinos do we see here?

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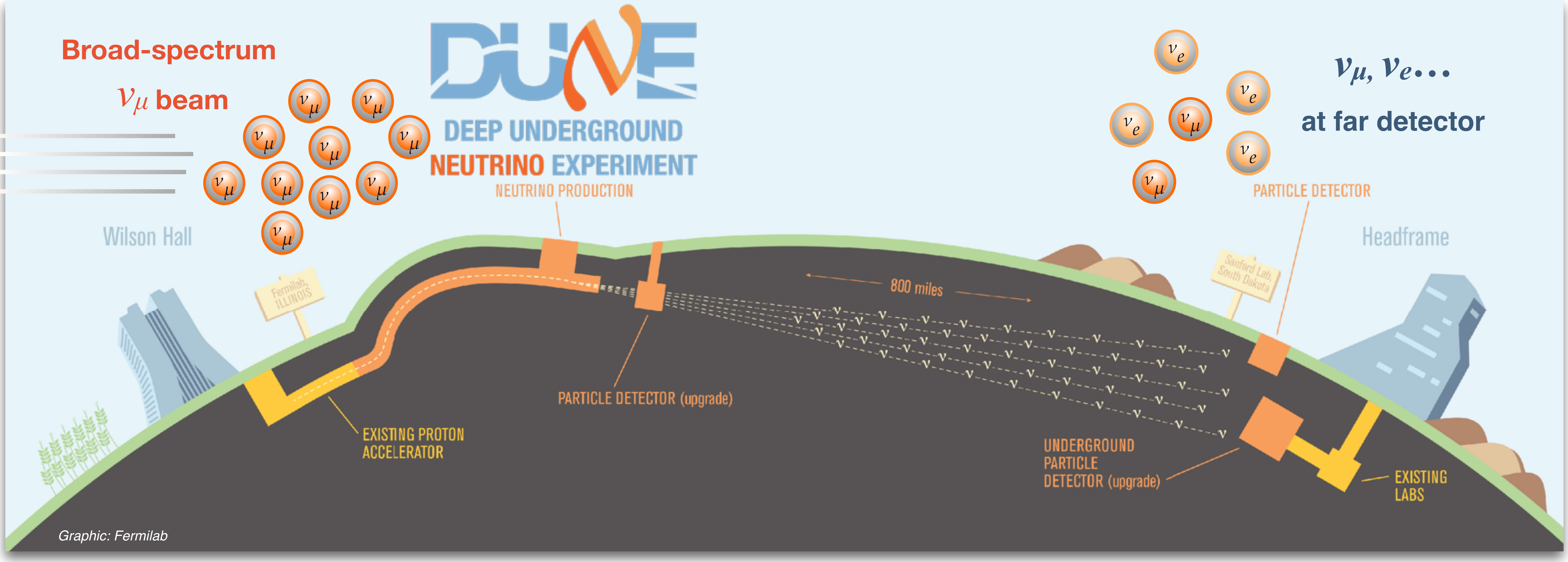


Graphic: Fermilab

How many neutrinos do we see here?

How many do we see here?
How does it compare to what we expect to see?

Exercise 2

Sounds easy! We can just…

1) Plot the energies of all the muon-neutrinos at Fermilab (near detector)

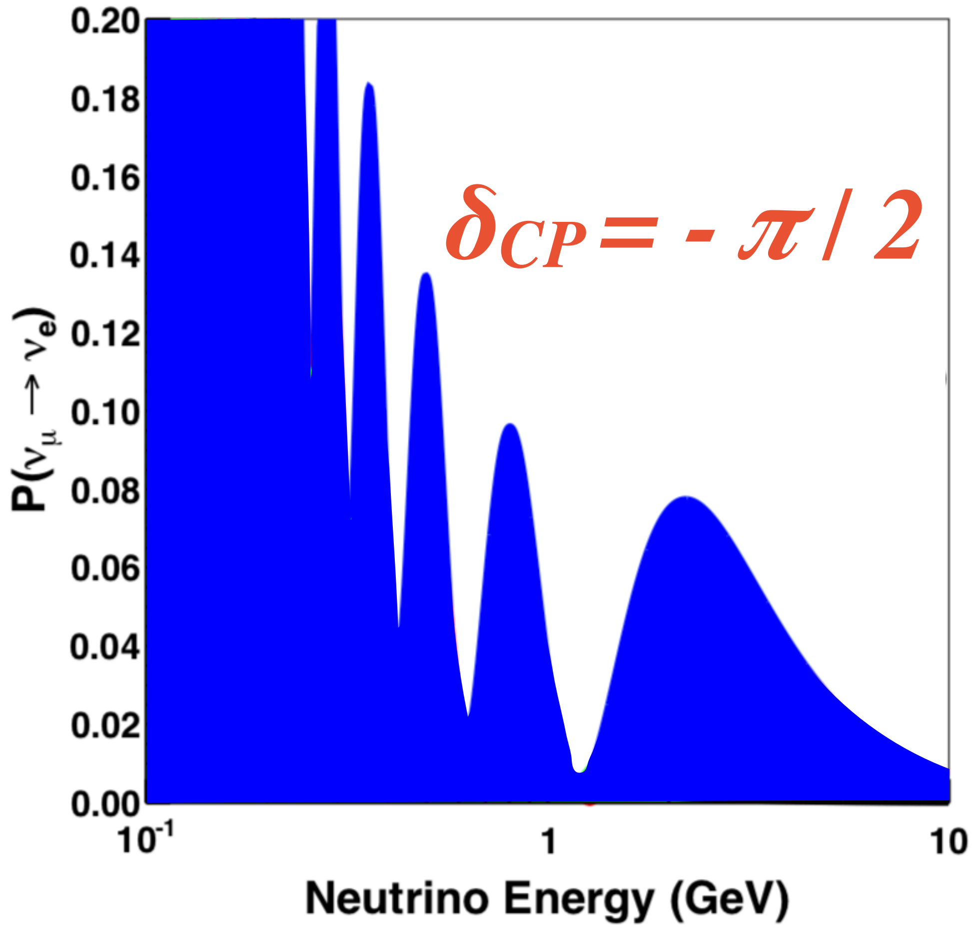
2) Plot the energies of all the electron-neutrinos at SURF (far detector)

3) Take the ratio of the two plots

4) Collect Nobel Prize

Photo: Reider Hahn

Photo: Sanford Underground Research Facility



Do you have a problem with that?

You should have a few problems with that! Discuss them with your team

Actually there are a few problems…

1) Plot the energies of all the muon-neutrinos at Fermilab

2) Plot the energies of all the electron-neutrinos at SURF

3) Take the ratio of the two plots

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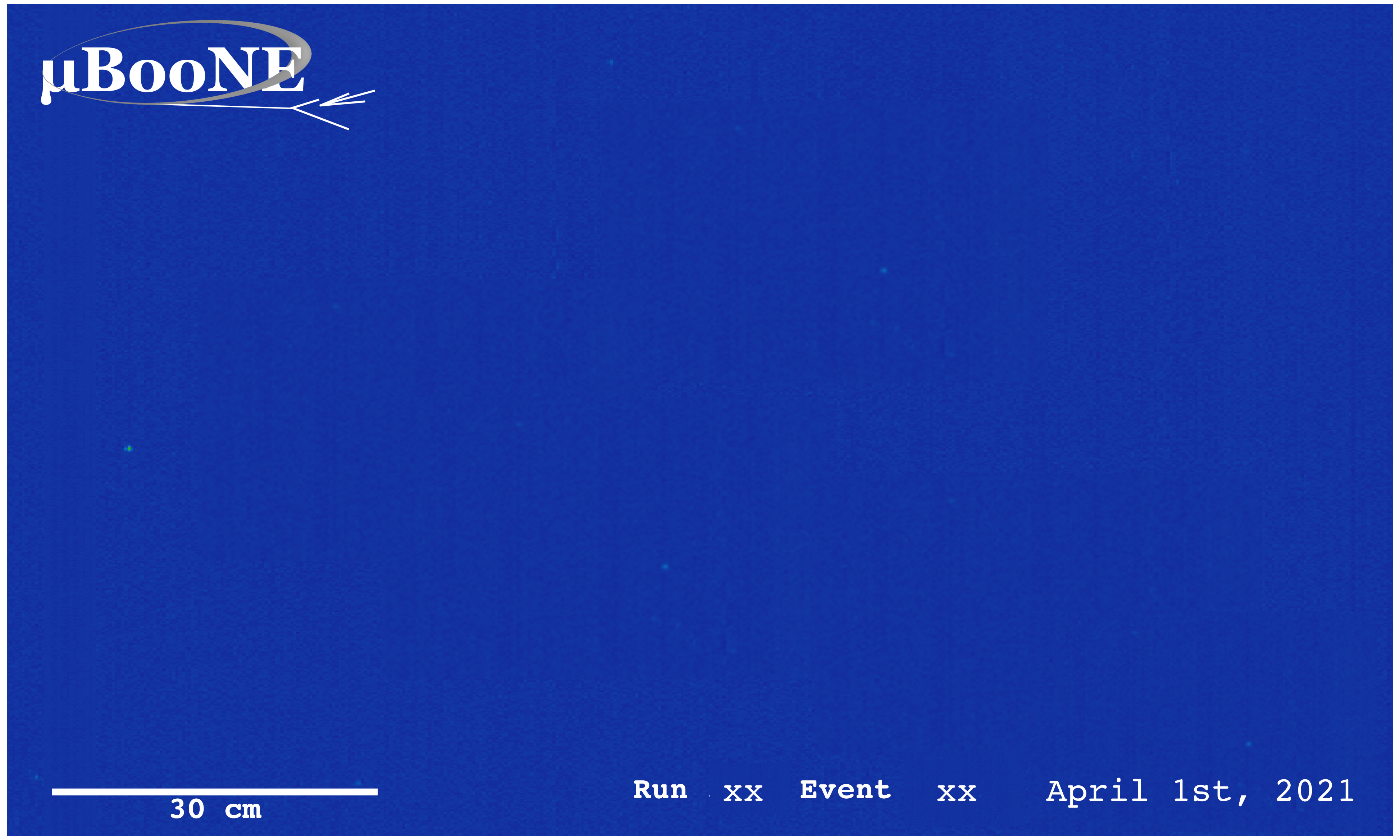
How do we detect a neutrino and know its **flavor**?
Neutrinos are invisible!



(Artist's impression of a detector with only neutrinos passing through it…)

Actually there are a few problems…

1) Plot the energies of all the muon-neutrinos at Fermilab

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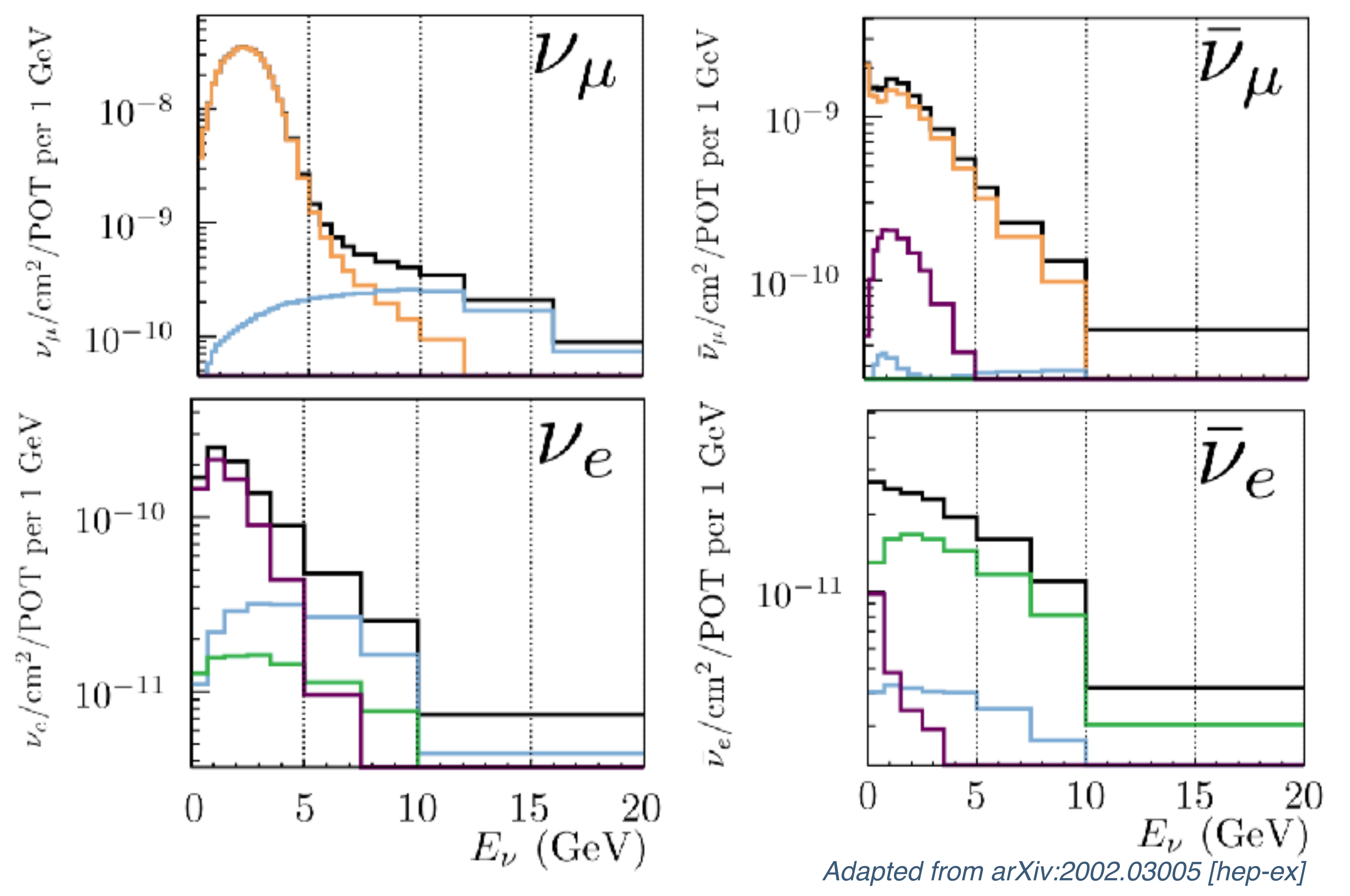
How do we know a neutrino's **energy**?
We have a broad-spectrum beam, that spreads as it travels.



Adapted from arXiv:2002.03005 [hep-ex]

Near-detector fluxes from different production mechanisms

Actually there are a few problems…

1) Plot the energies of all the muon-neutrinos at Fermilab

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How do we detect a neutrino and know its **flavor**?
Neutrinos are invisible!

How do we know a neutrino's **energy**?
We have a broad-spectrum beam, that spreads as it travels.

How do we know we have detected **all** the neutrinos?
Beams spread, detector designs differ, efficiencies are energy-dependent…

We can only detect neutrinos if they interact!

and

We can only understand neutrinos if we understand their interactions

How many oscillated neutrinos do we see?

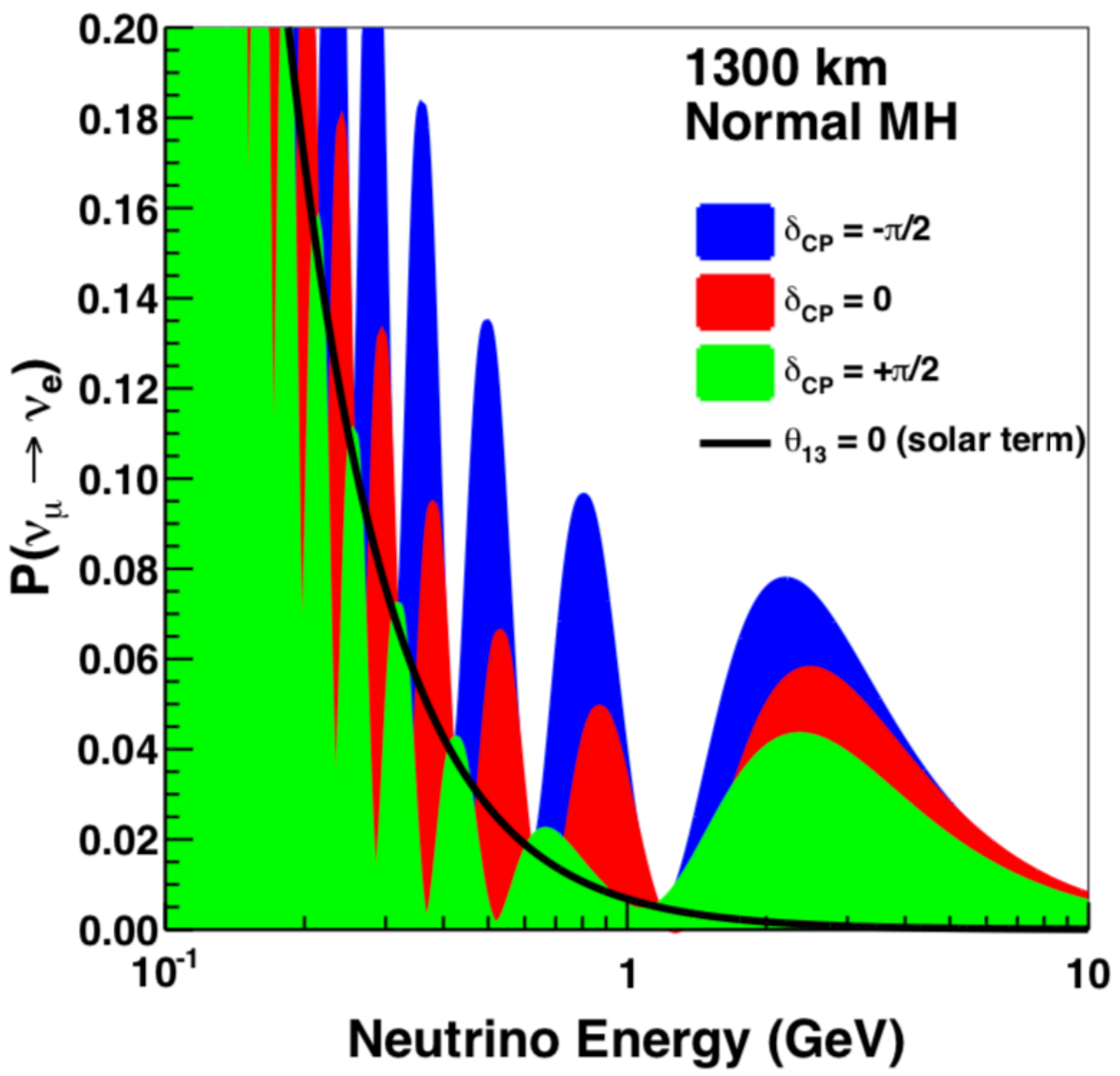
$$R_{\mu\rightarrow e}(E_{\text{rec}}) = N \int dE_\nu \Phi_\mu(E_\nu) P_{\nu_\mu\rightarrow\nu_e}(E_\nu)\sigma_e(E_\nu, E_{\text{rec}})\epsilon_e(E_\nu)$$

How many oscillated neutrinos do we see?

What we want to know

$$R_{\mu\to e}(E_{\text{rec}}) = N\int dE_\nu \Phi_\mu(E_\nu) \boxed{P_{\nu_\mu\to\nu_e}(E_\nu)} \sigma_e(E_\nu, E_{\text{rec}})\epsilon_e(E_\nu)$$

Probability of a neutrino oscillating, as a function of its true energy



How many oscillated neutrinos do we see?

What we measure

What we want to know

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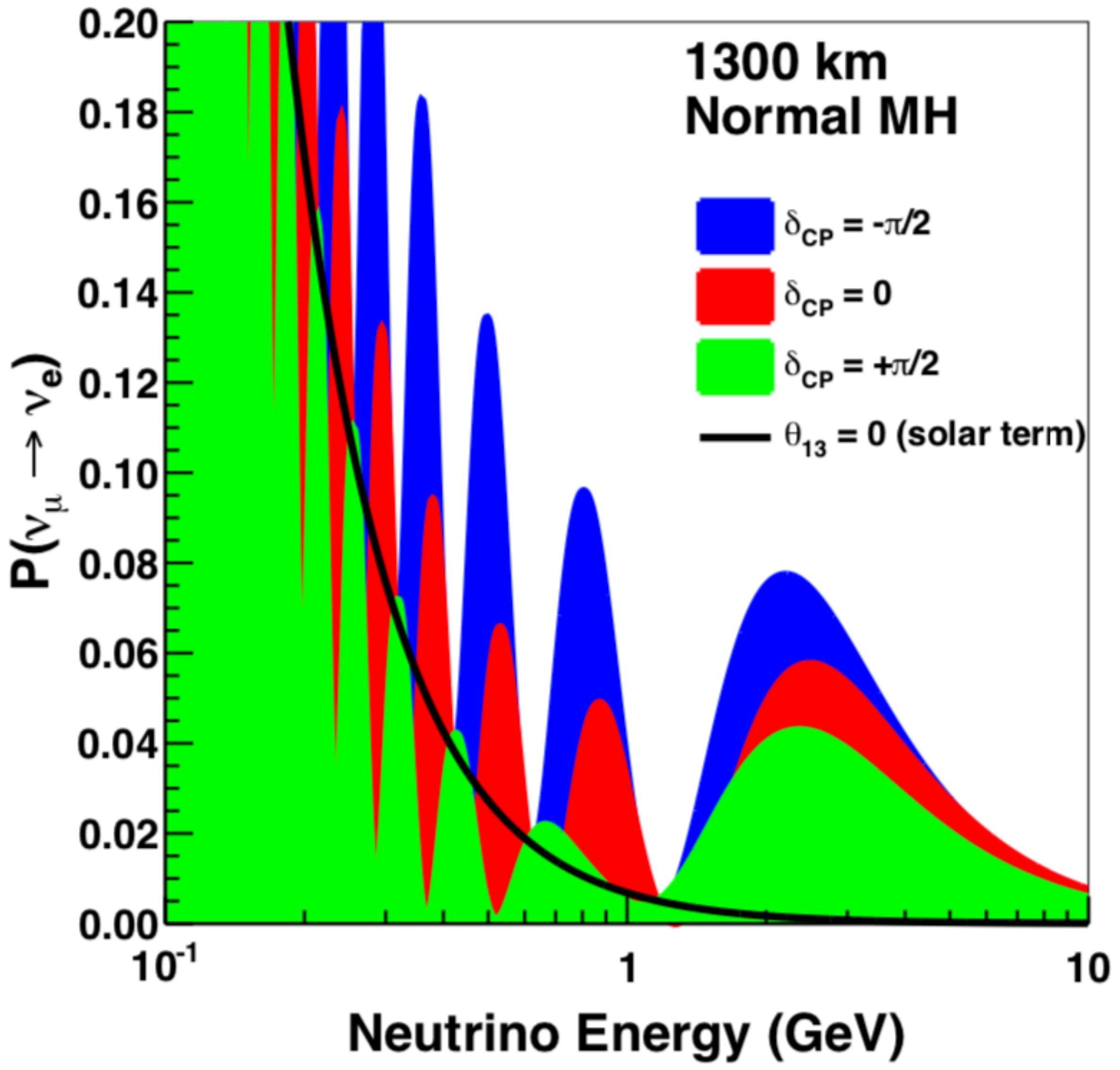
Oscillated neutrinos detected, as a function of measured energy

Probability of a neutrino oscillating, as a function of its true energy



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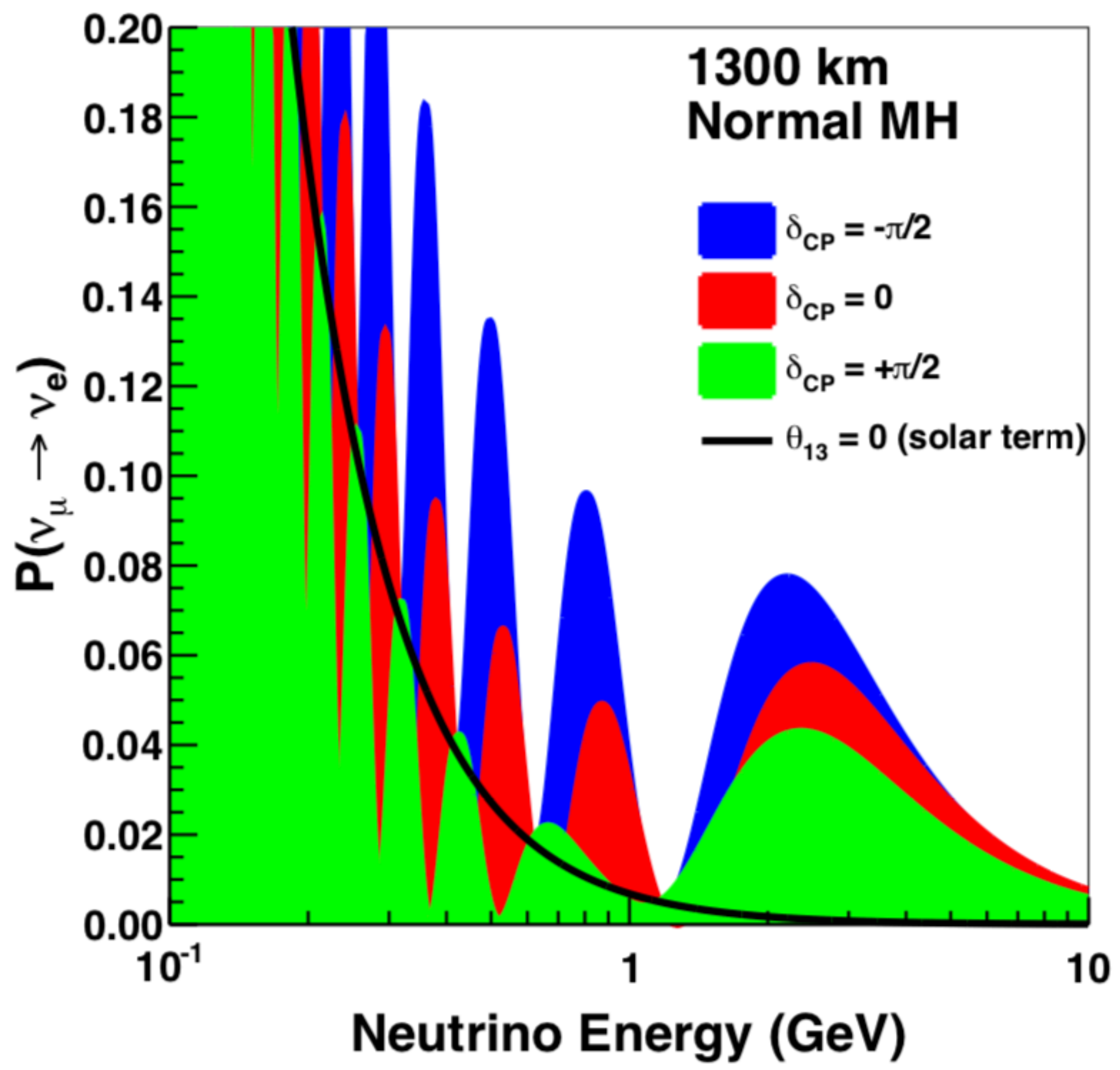
Oscillated neutrinos detected, as a function of measured energy

Probability of a neutrino oscillating, as a function of its true energy

Not necessarily the same! We have to reconstruct the invisible neutrino's energy



How many oscillated neutrinos do we see?

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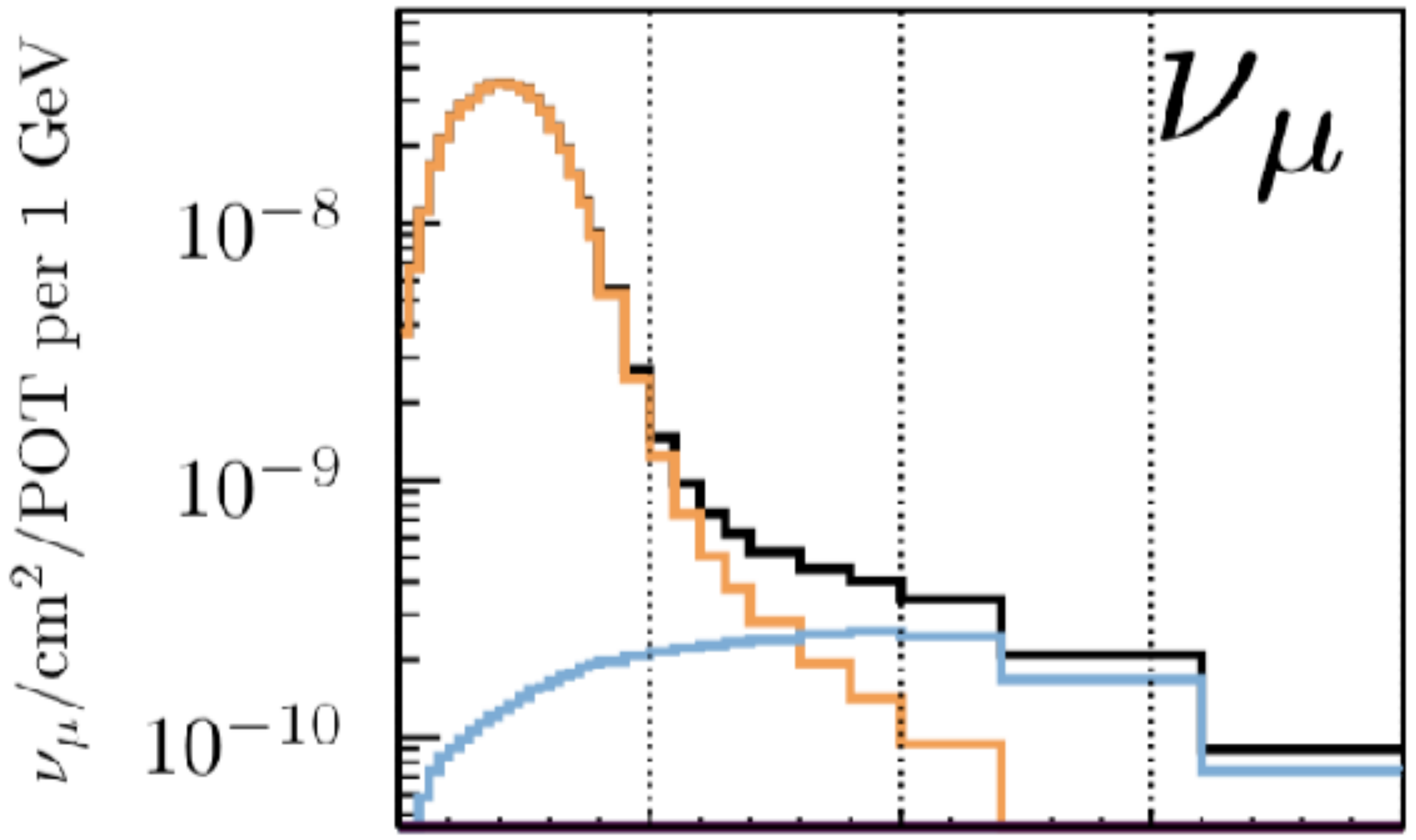
Oscillated neutrinos detected, as a function of measured energy

Flux (energy spectrum) of unoscillated neutrinos

Probability of a neutrino oscillating, as a function of its true energy



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What we measure

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Oscillated neutrinos detected, as a function of measured energy

Flux (energy spectrum) of unoscillated neutrinos

Probability of a neutrino oscillating, as a function of its true energy

Detector efficiency - the chance of successfully detecting a neutrino if it interacts

How many oscillated neutrinos do we see?

What we measure

What we want to know

$$R_{\mu\to e}(E_{\text{rec}}) = N\int dE_\nu \Phi_\mu(E_\nu) P_{\nu_\mu\to\nu_e}(E_\nu)\sigma_e(E_\nu, E_{\text{rec}})\epsilon_e(E_\nu)$$

Oscillated neutrinos detected, as a function of measured energy

Flux (energy spectrum) of unoscillated neutrinos

Probability of a neutrino oscillating, as a function of its true energy

Interaction cross section - the probability a neutrino interacts, and the amount of its energy we can detect

Detector efficiency - the chance of successfully detecting a neutrino if it interacts

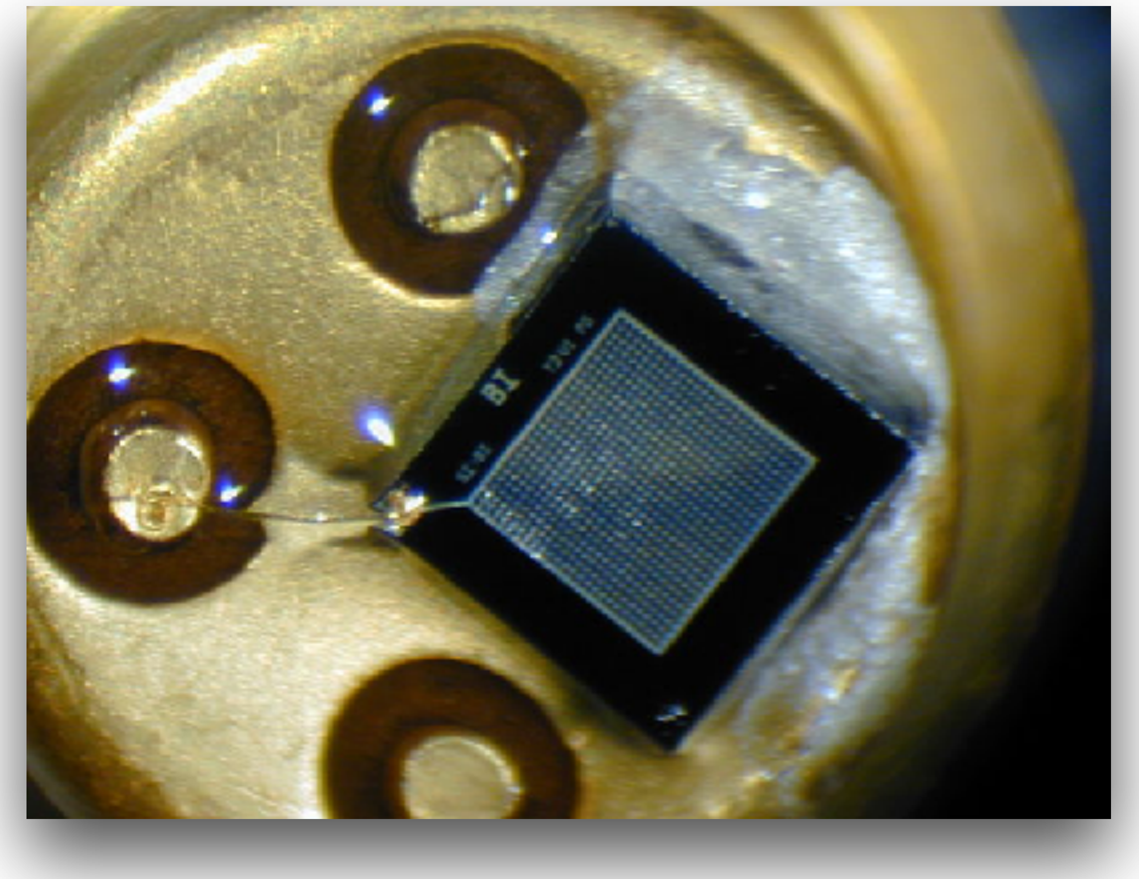
↑

Very complicated - and the subject of this talk!

How do we detect particles?

Photo: SuperNEMO

Photomultiplier tubes and **silicon photomultipliers (SIPMs)**

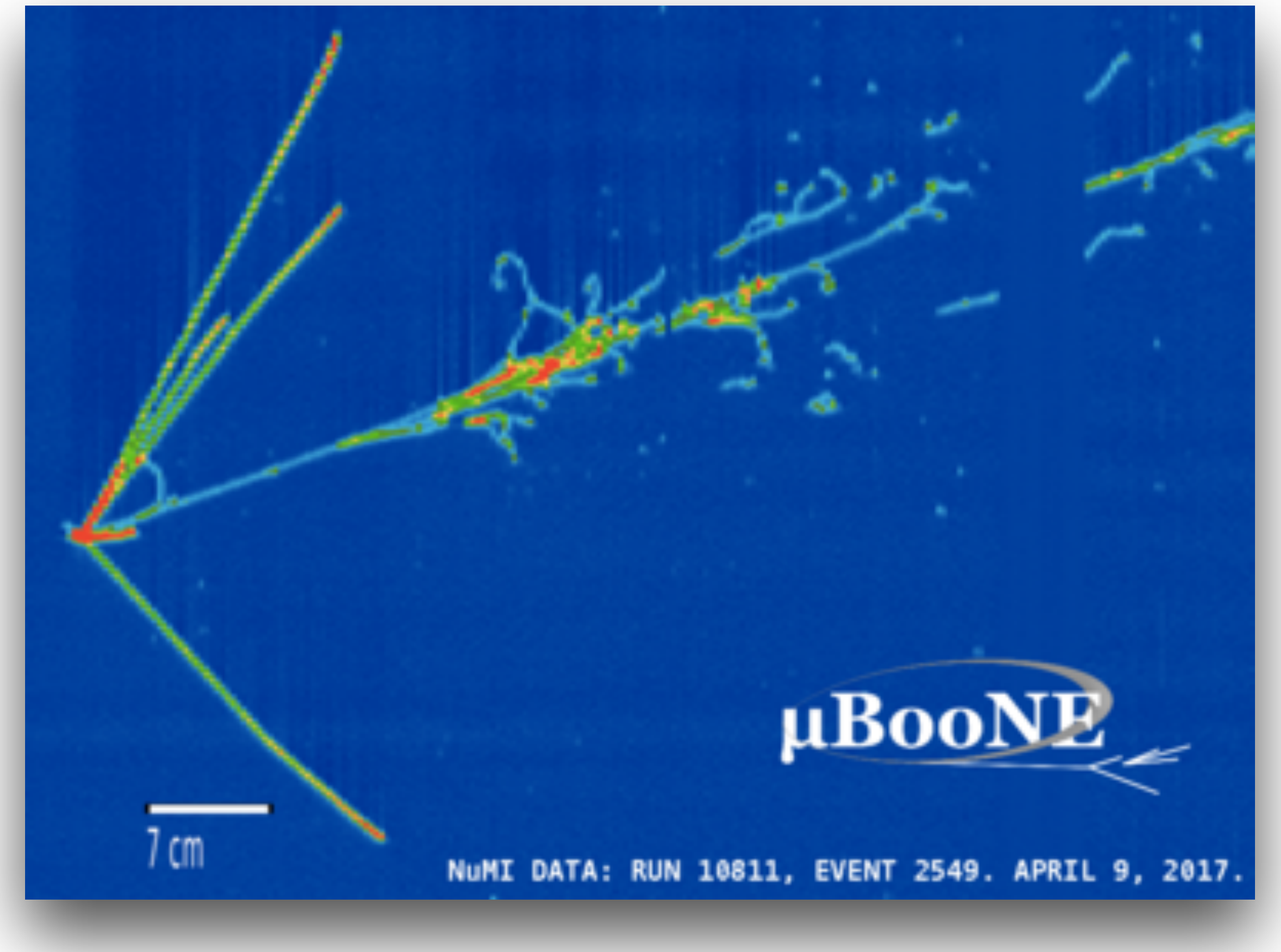


measure **photons**' energy

Charged particles

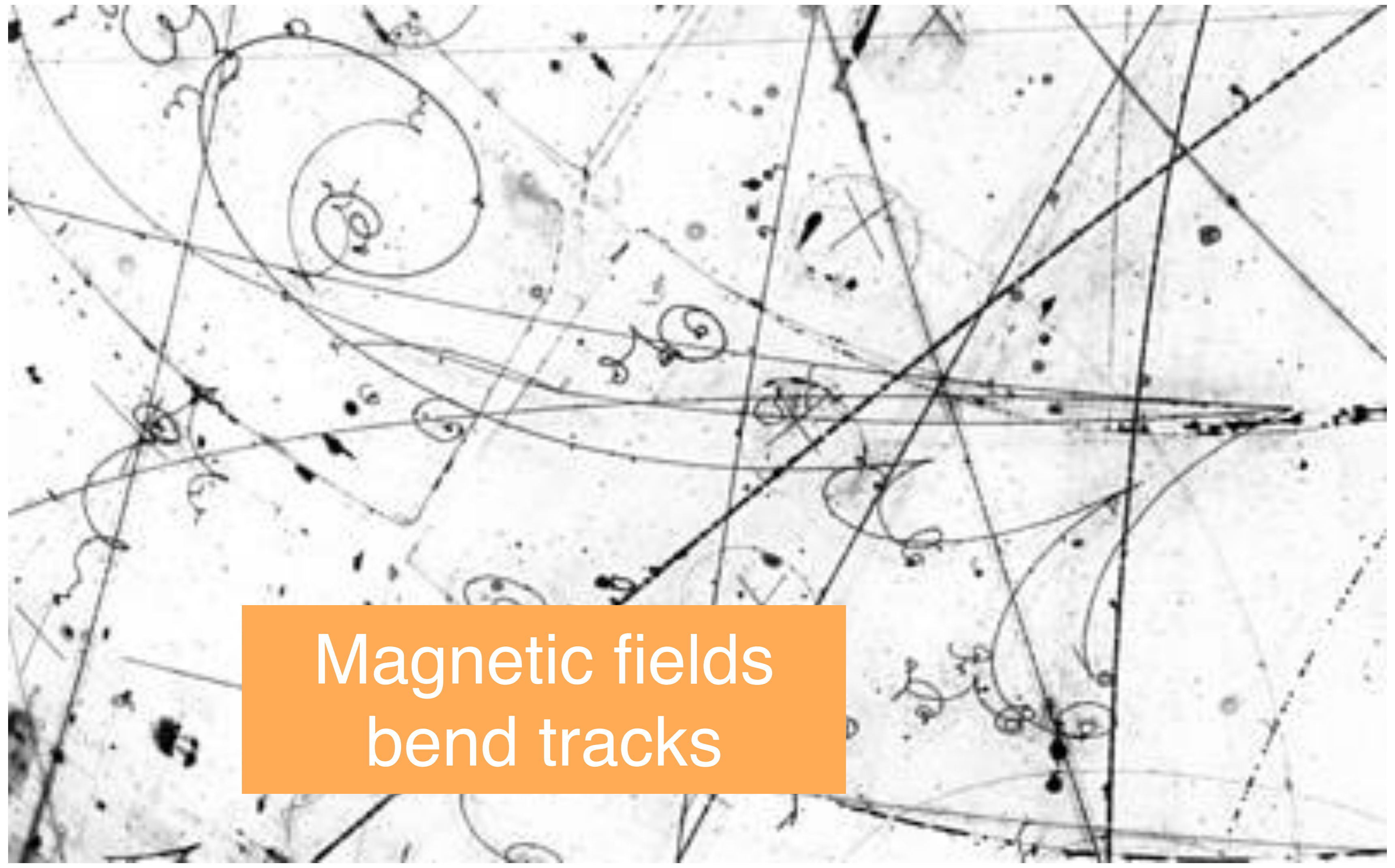
produce light in **scintillators** (e.g. SAND)

use ionization to generate tracks in **time-projection chambers** (e.g. ND-GAr, ND-LAr)



What can we learn from tracks?

Curvature
(if there are magnets)

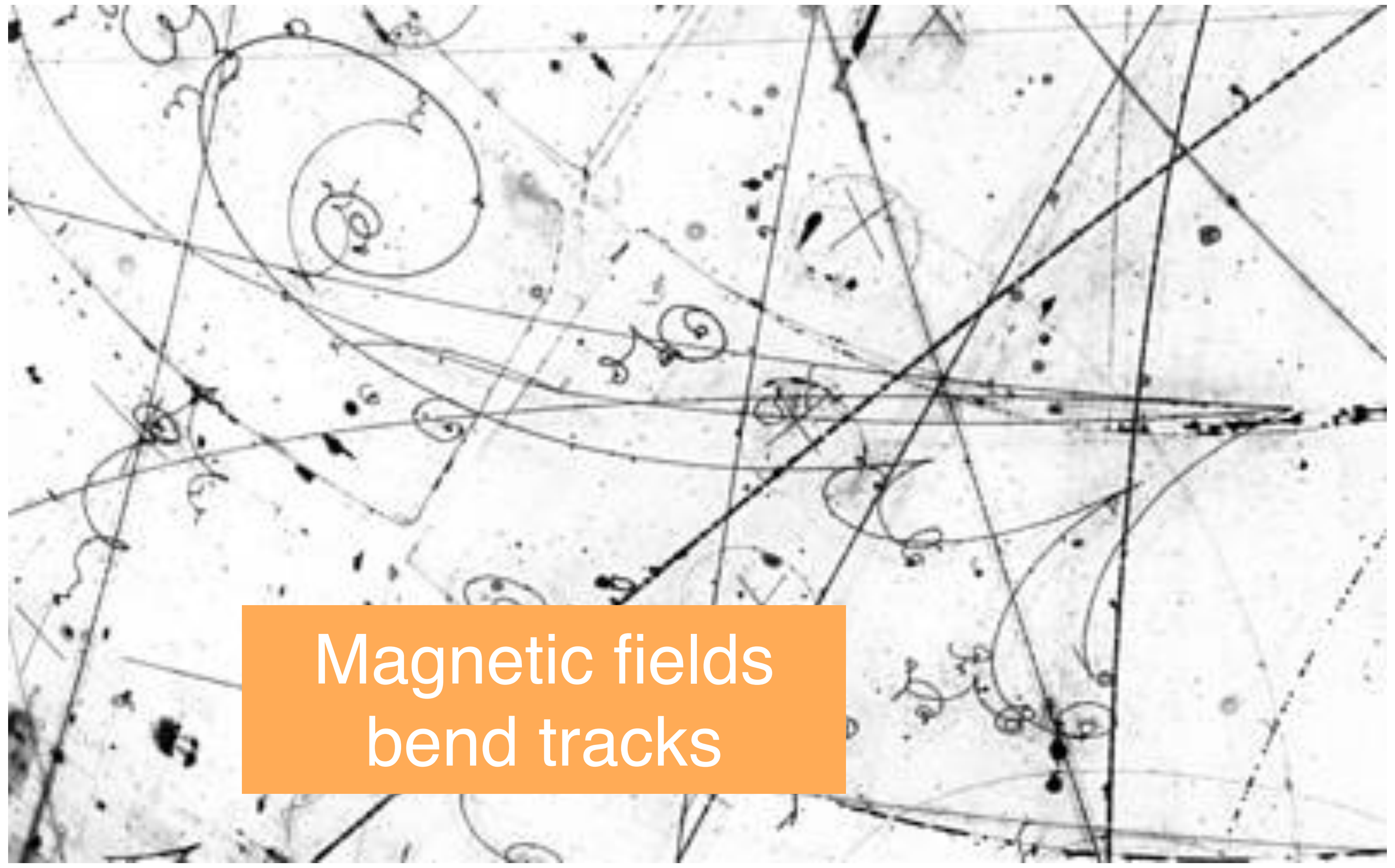


Magnetic fields
bend tracks

What can we learn from tracks?

Curvature
(if there are magnets)

Track shape (length,
sharpness, dE/dx)



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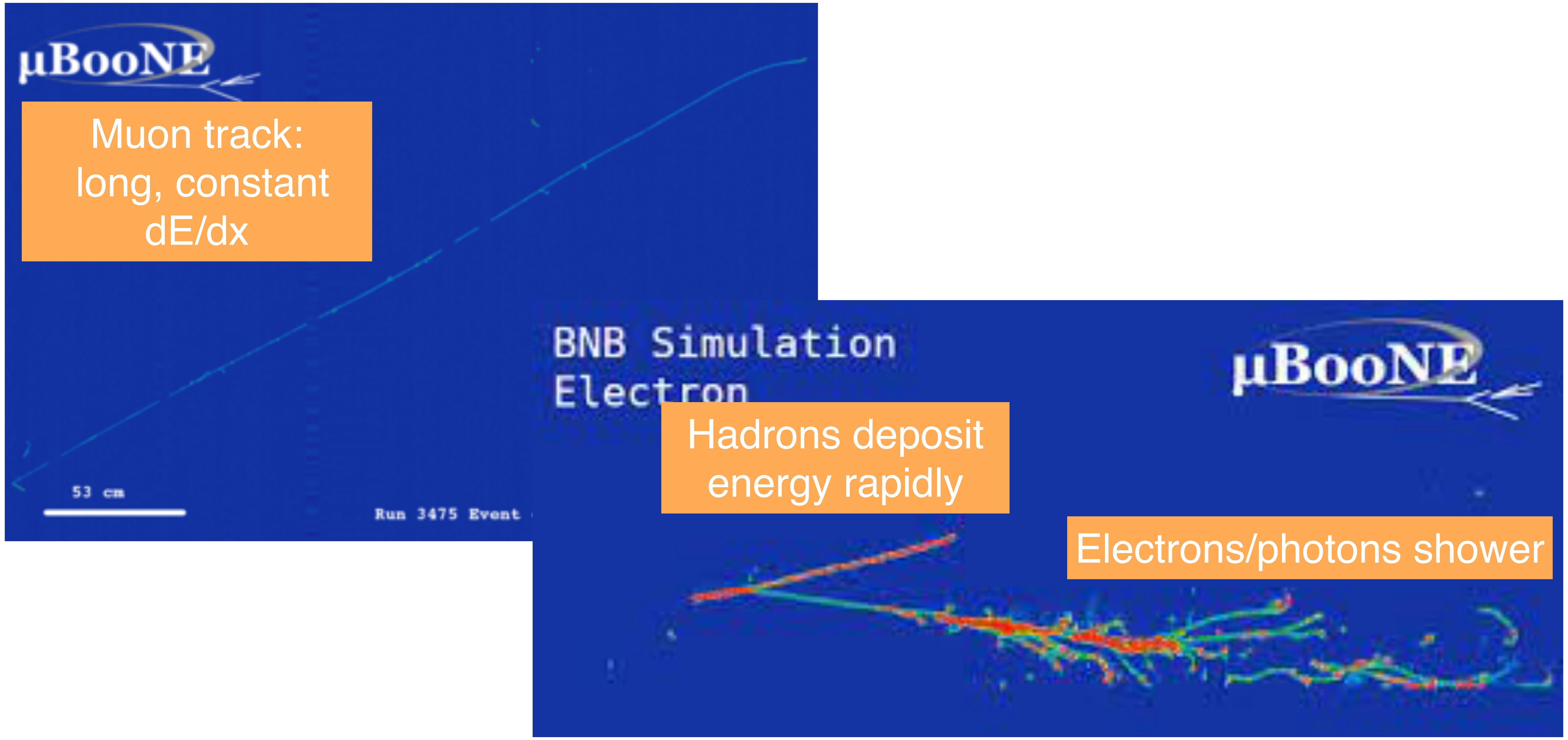


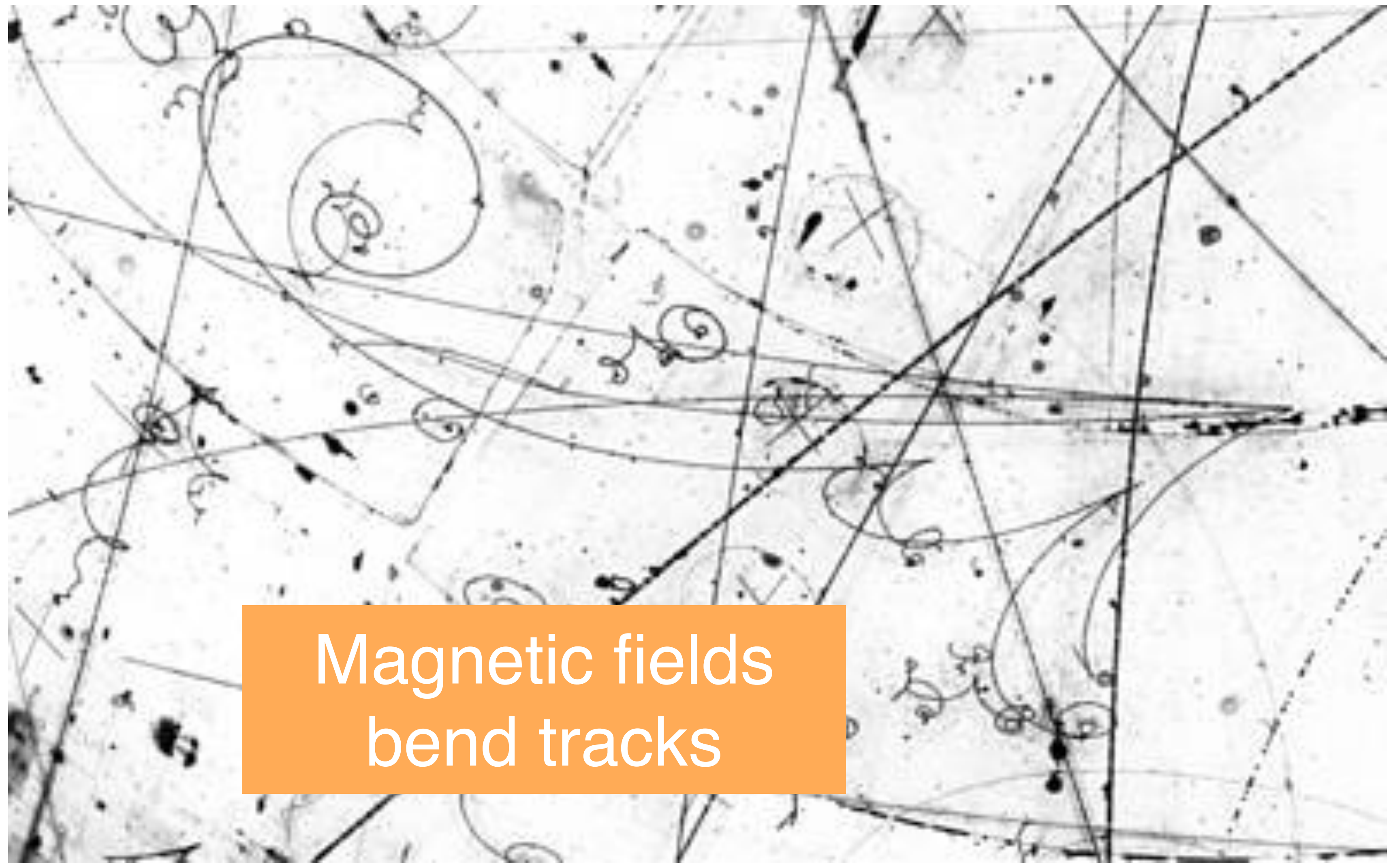
Muon track: long, constant dE/dx

Hadrons deposit energy rapidly

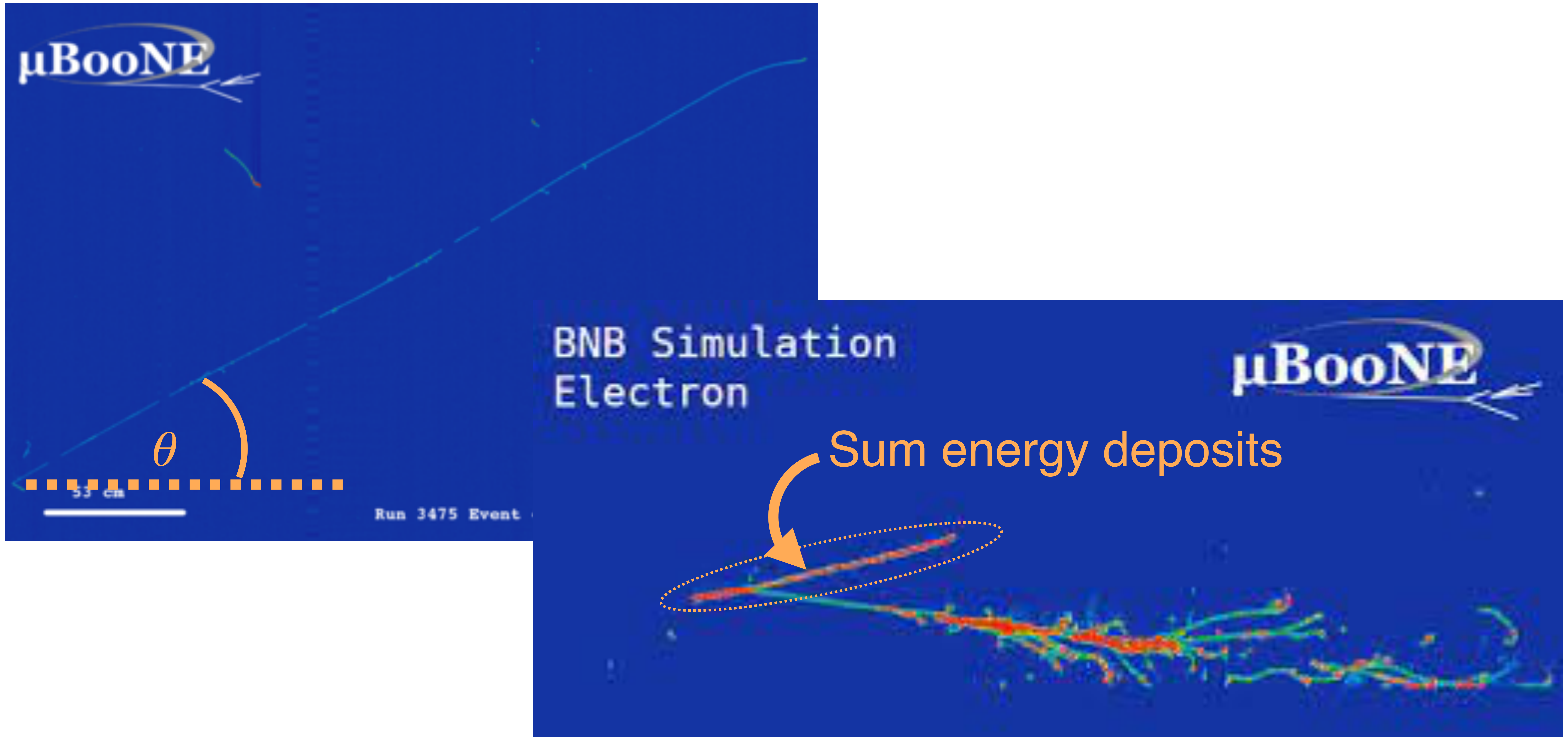
Electrons/photons shower

What can we learn from tracks?

- Curvature (if there are magnets)
- Track shape (length, sharpness, dE/dx)
- Direction
- Energy

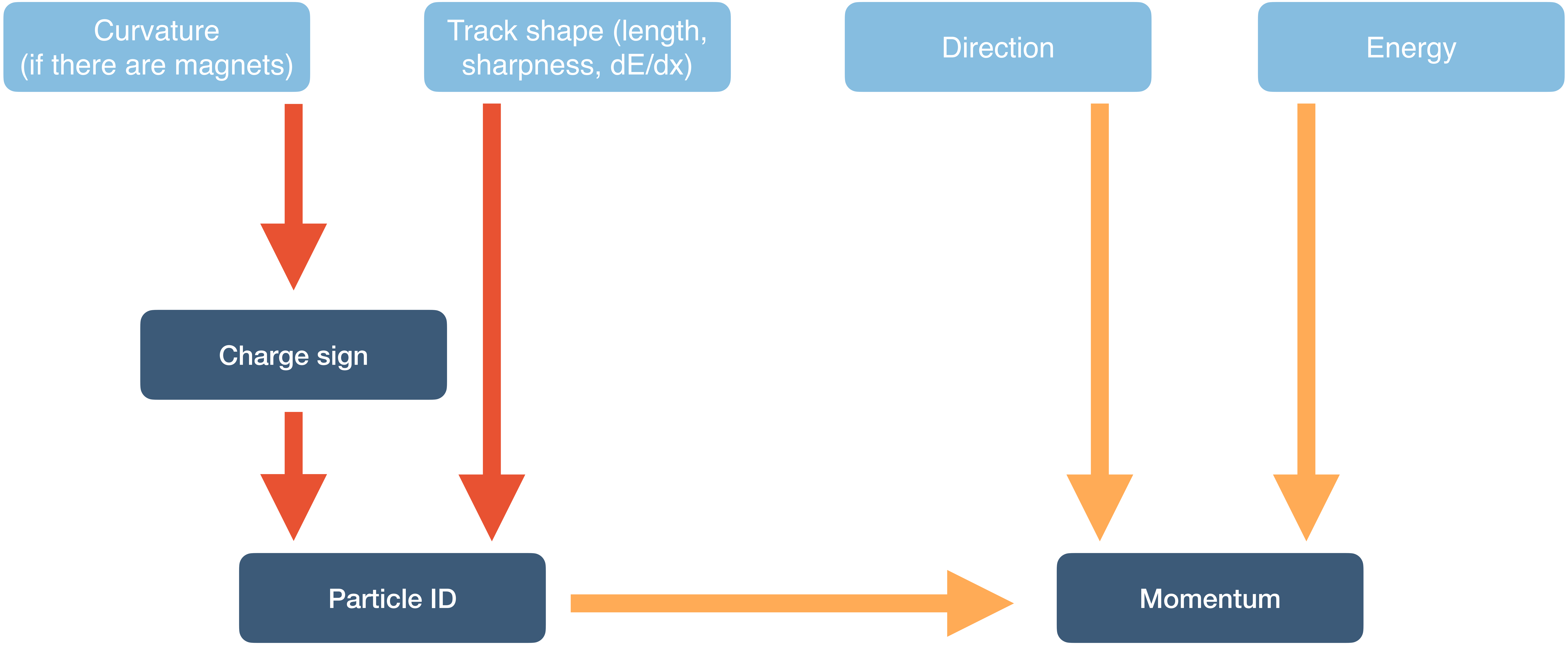


Magnetic fields bend tracks



Sum energy deposits

What can we learn from tracks?



Curvature
(if there are magnets)

Track shape (length, sharpness, dE/dx)

Direction

Energy

Charge sign

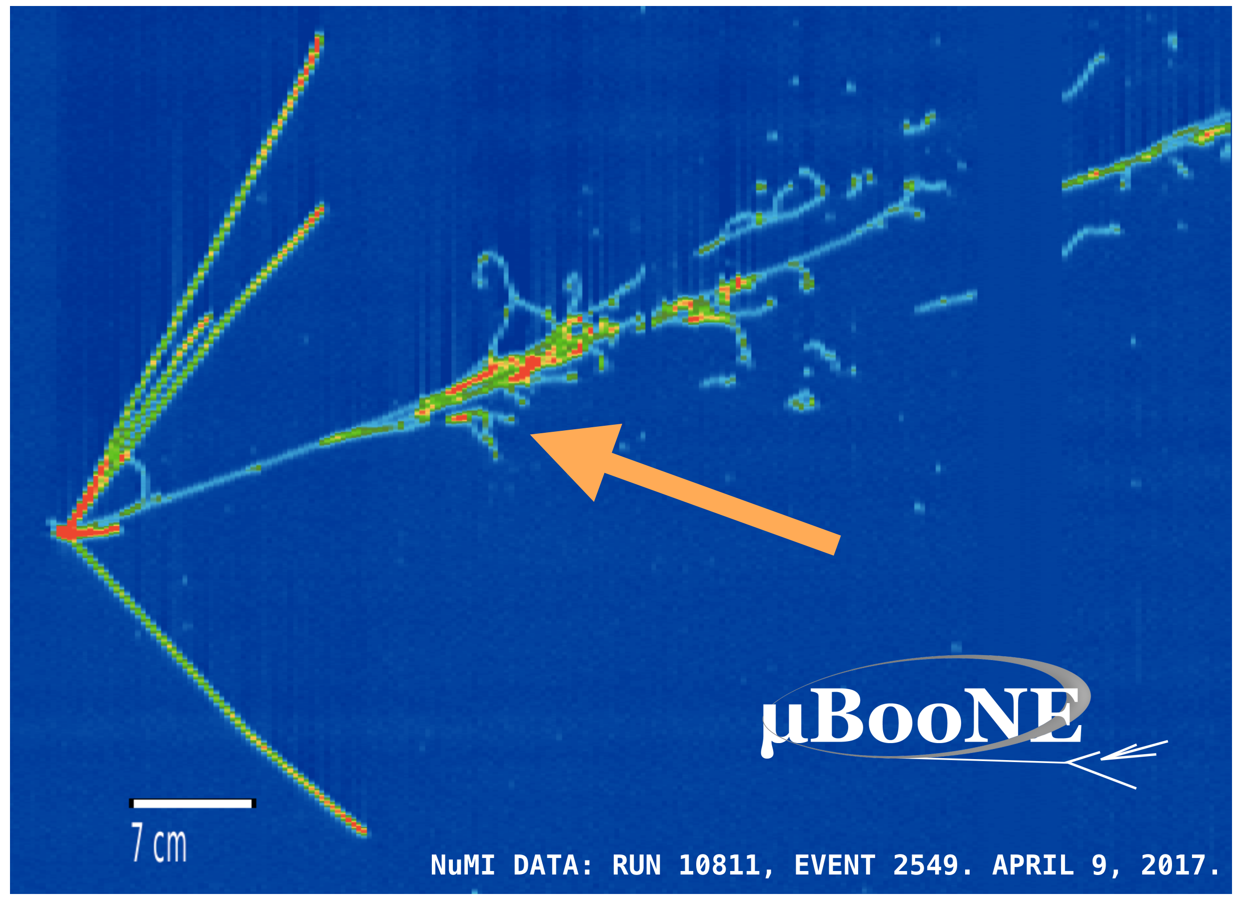
Particle ID

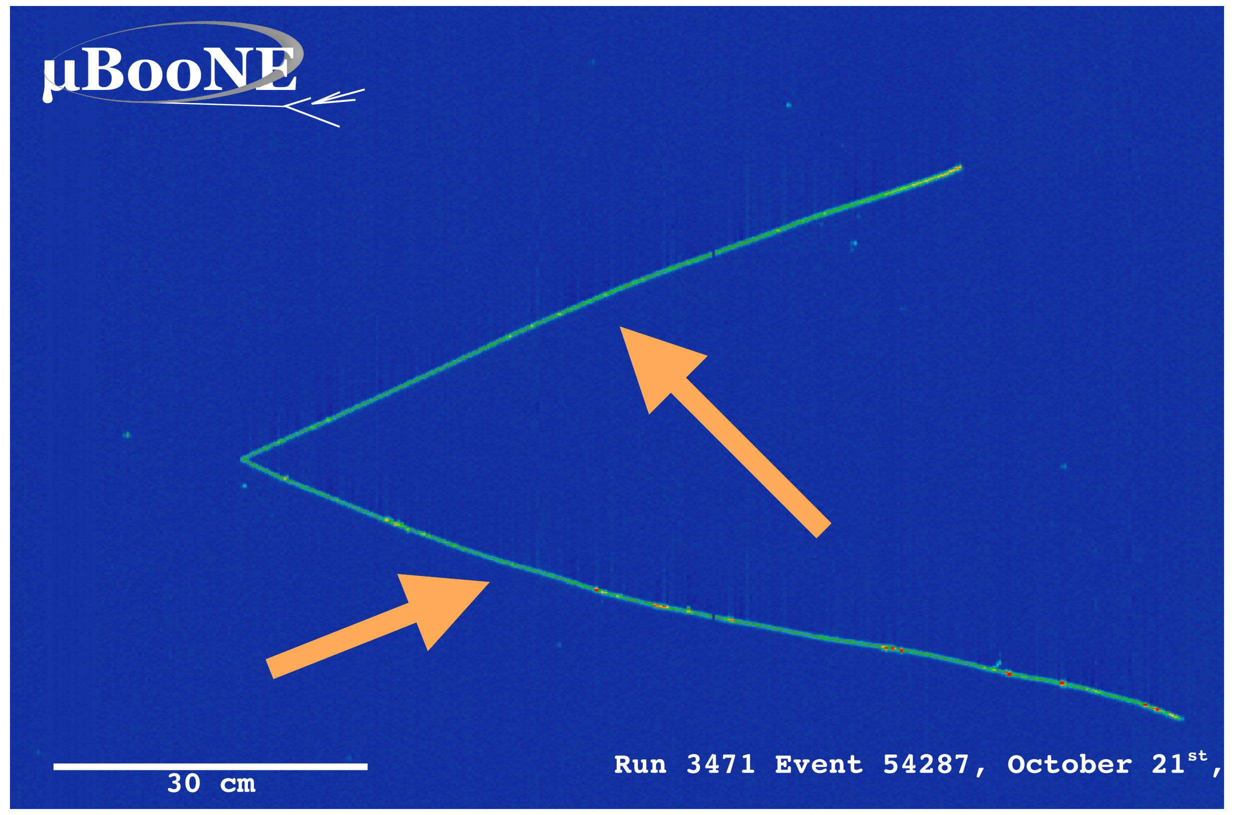
Momentum

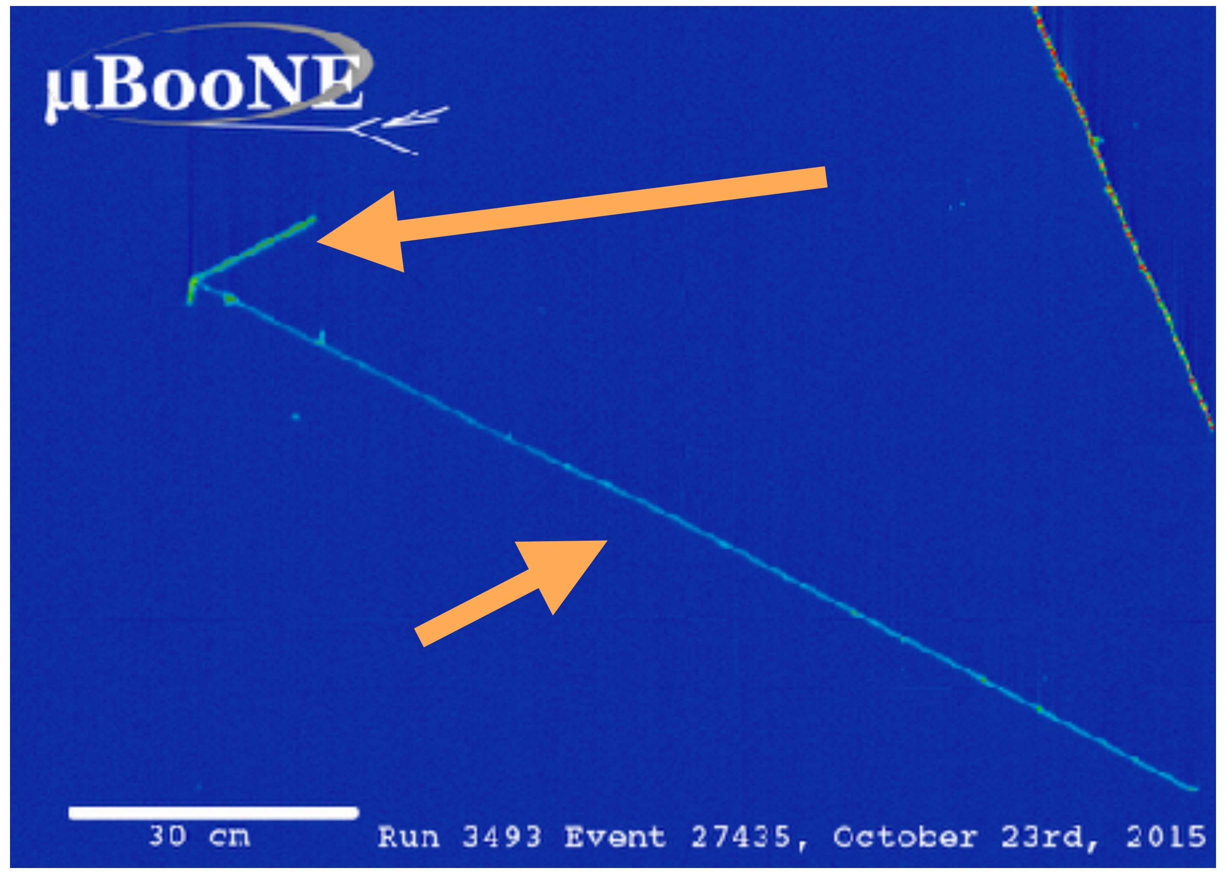
Puzzle - Spot the particles

μ^-	Muon
p	Proton
e^-	Electron
$\pi^\pm$	Charged pion
ν_μ	Muon neutrino
ν_e	Electron neutrino

Exercise 3







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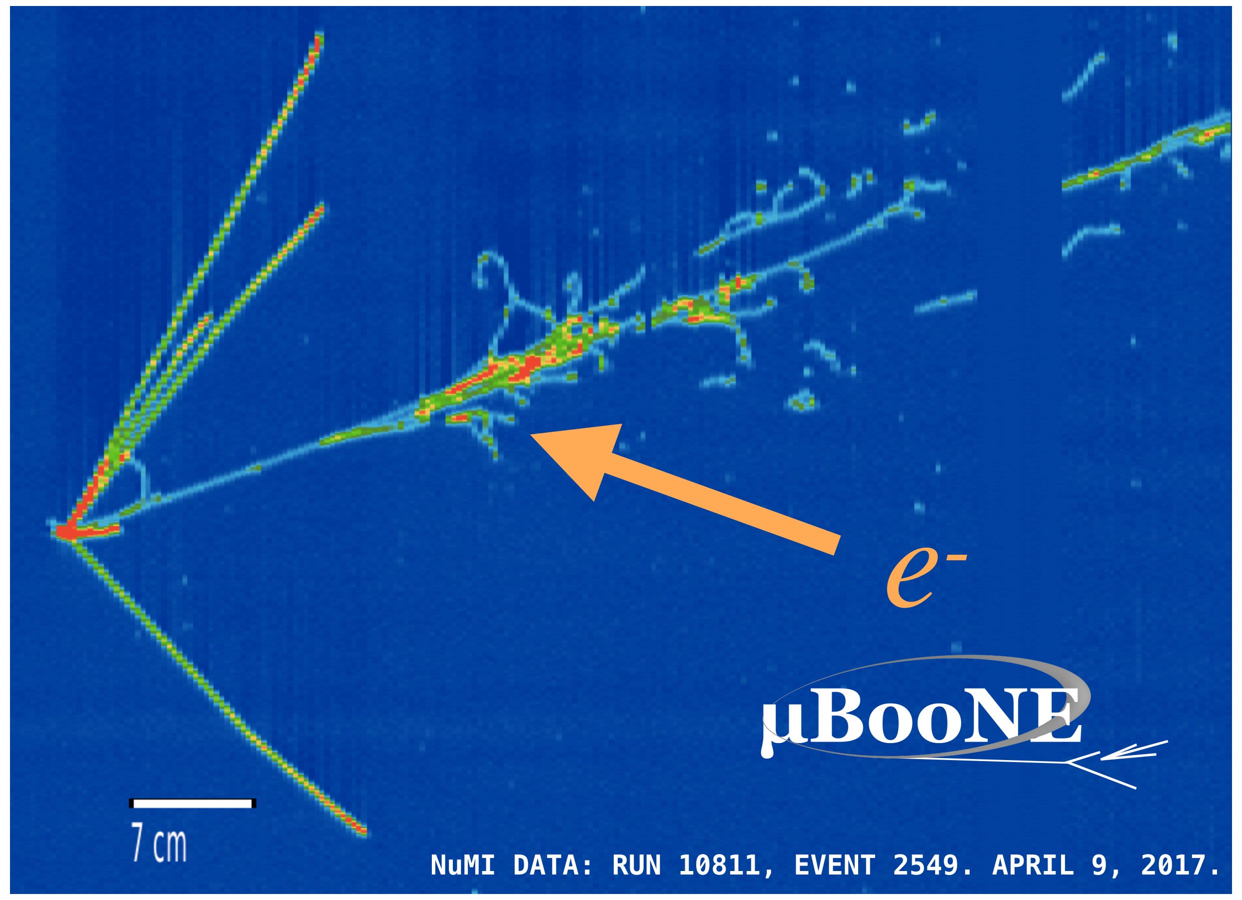

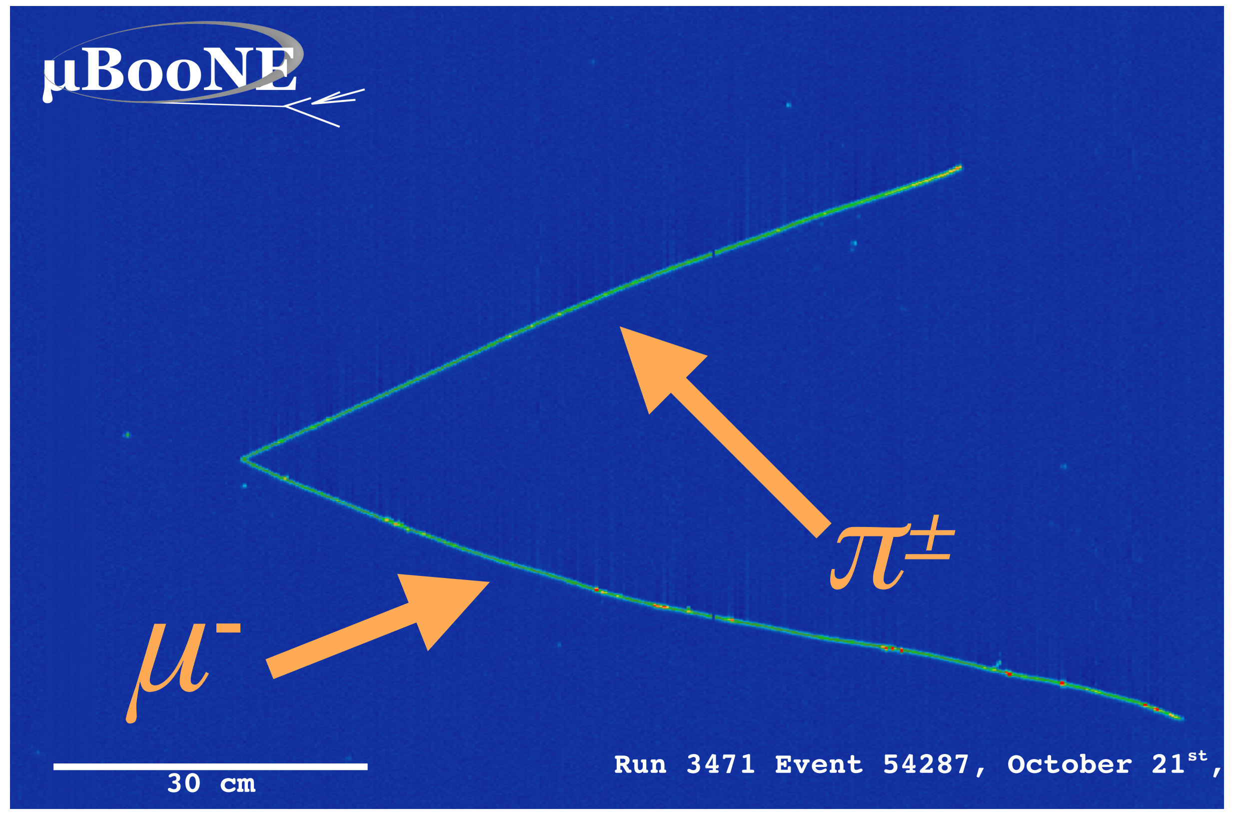

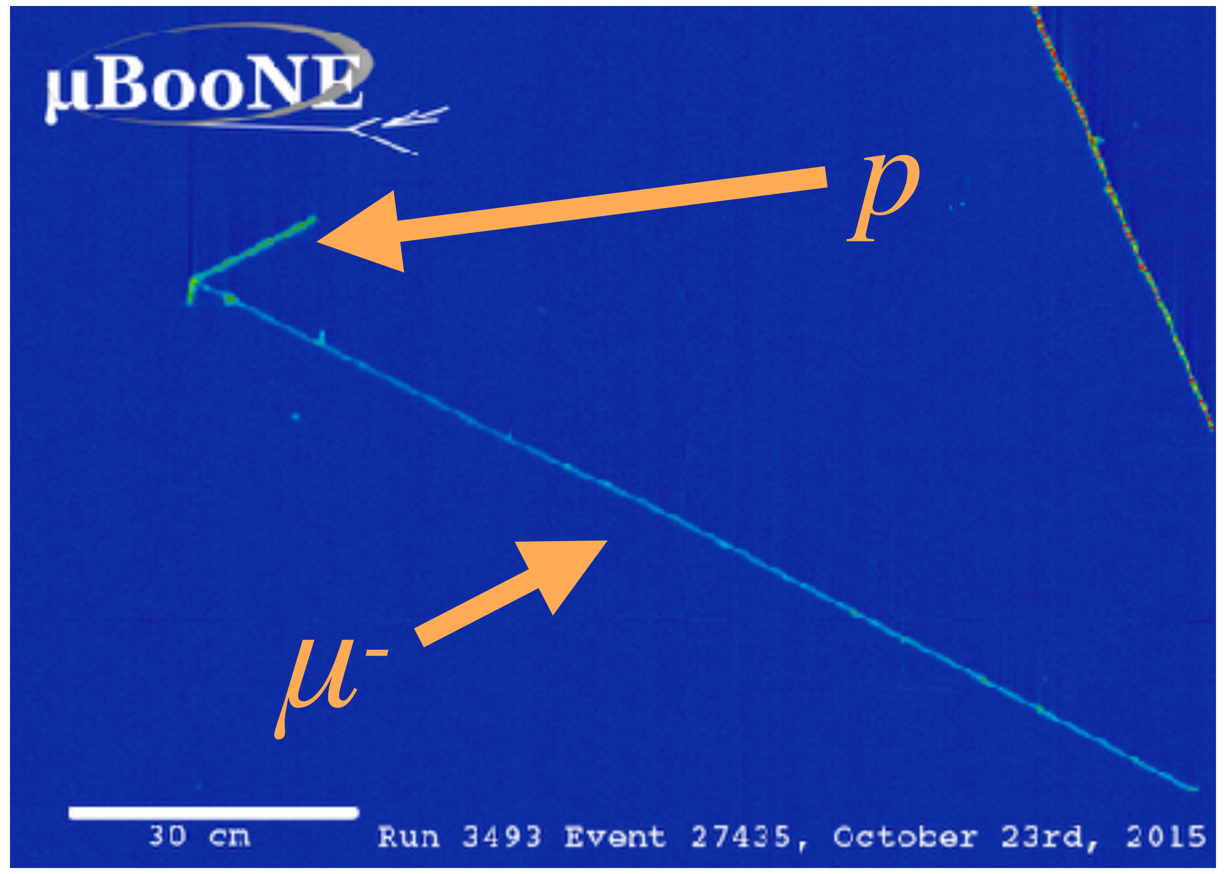

Puzzle - Spot the particles

μ^-	Muon
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ν_μ	Muon neutrino
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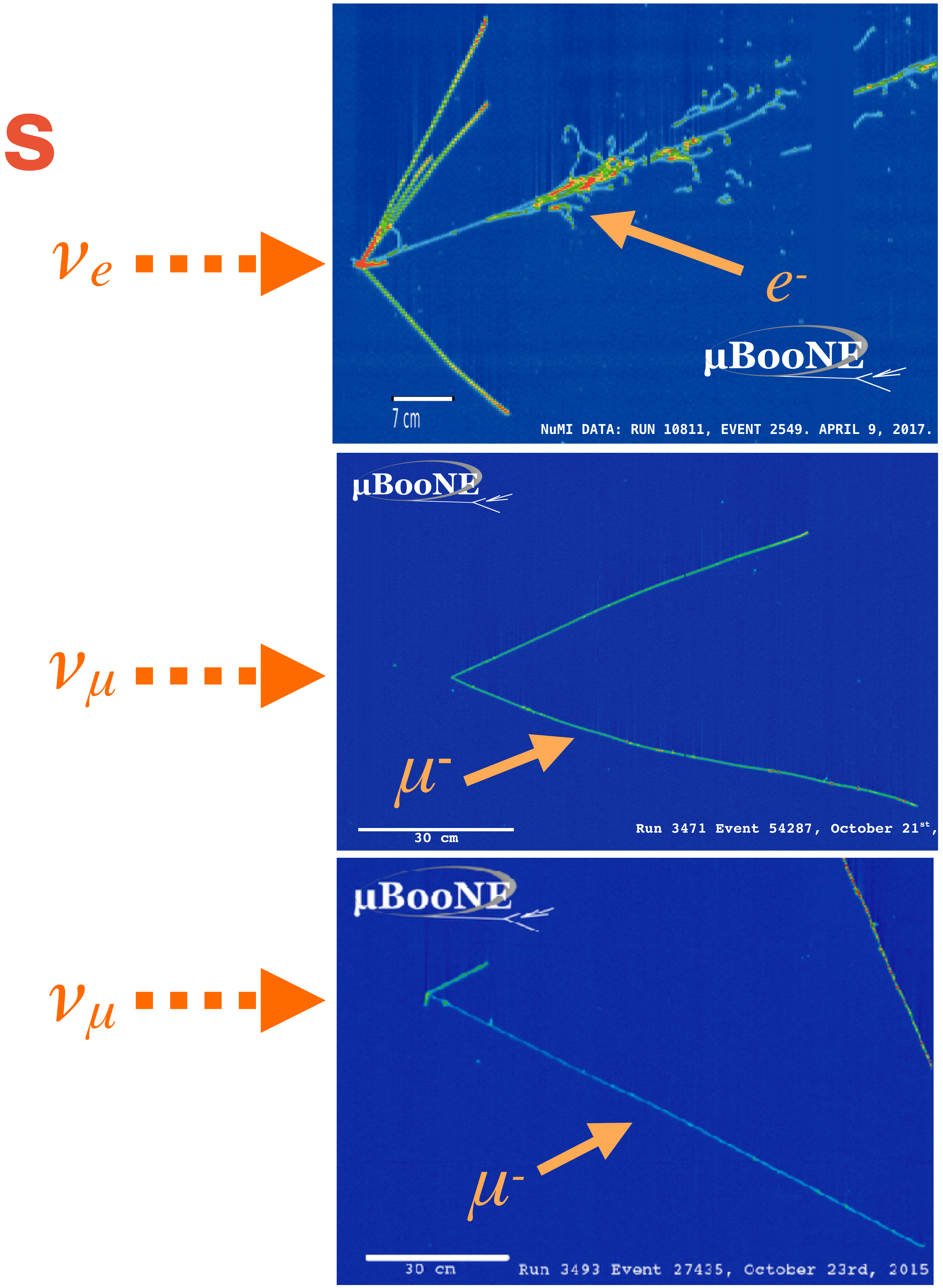
Exercise 3

The neutrinos are invisible
we can only “see” them through their interaction products

Lepton flavour is conserved



We can detect a neutrino… if it interacts!

What do we want to know about it?

Particle ID

Momentum

We can detect a neutrino… if it interacts!

Question 1

What do we want to know about it?

Particle ID
(flavor)

Momentum

Neutrinos interact via the **weak interaction**.
For each flavor, there are two possible vertices:
charged current and **neutral current**

- Can you draw the vertices?
- Which will help you discover the neutrino’s flavor?

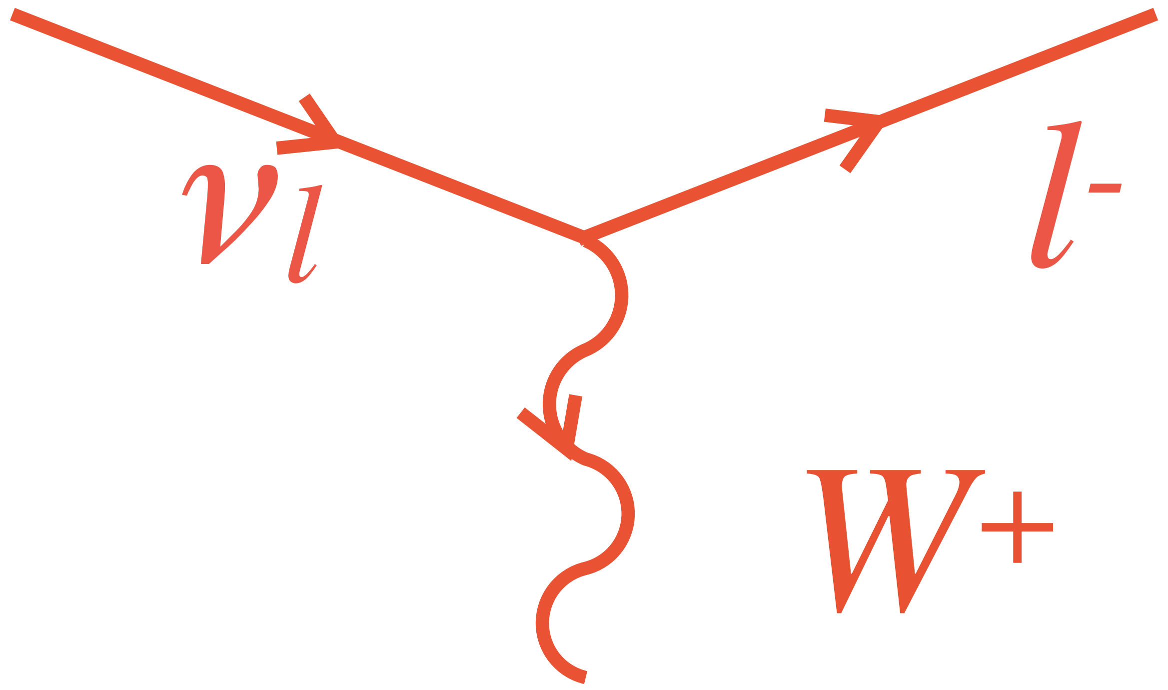
We can detect a neutrino… if it interacts!

What do we want to know about it?

Particle ID (flavor)

Momentum

Charged-current interaction



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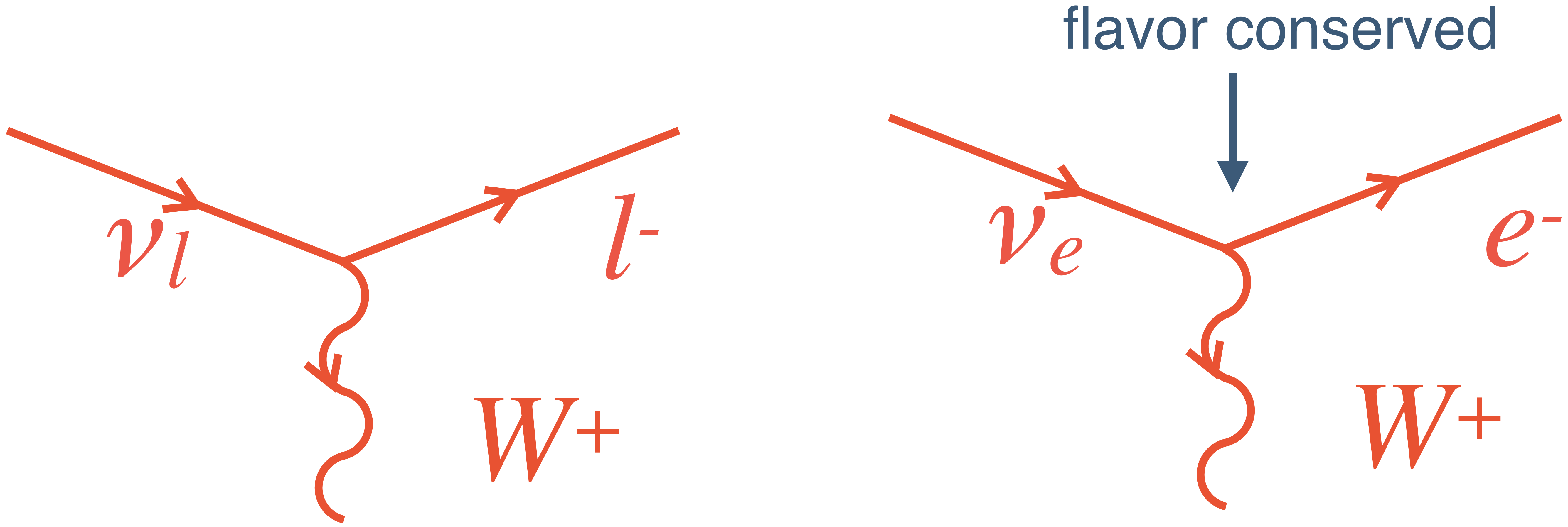

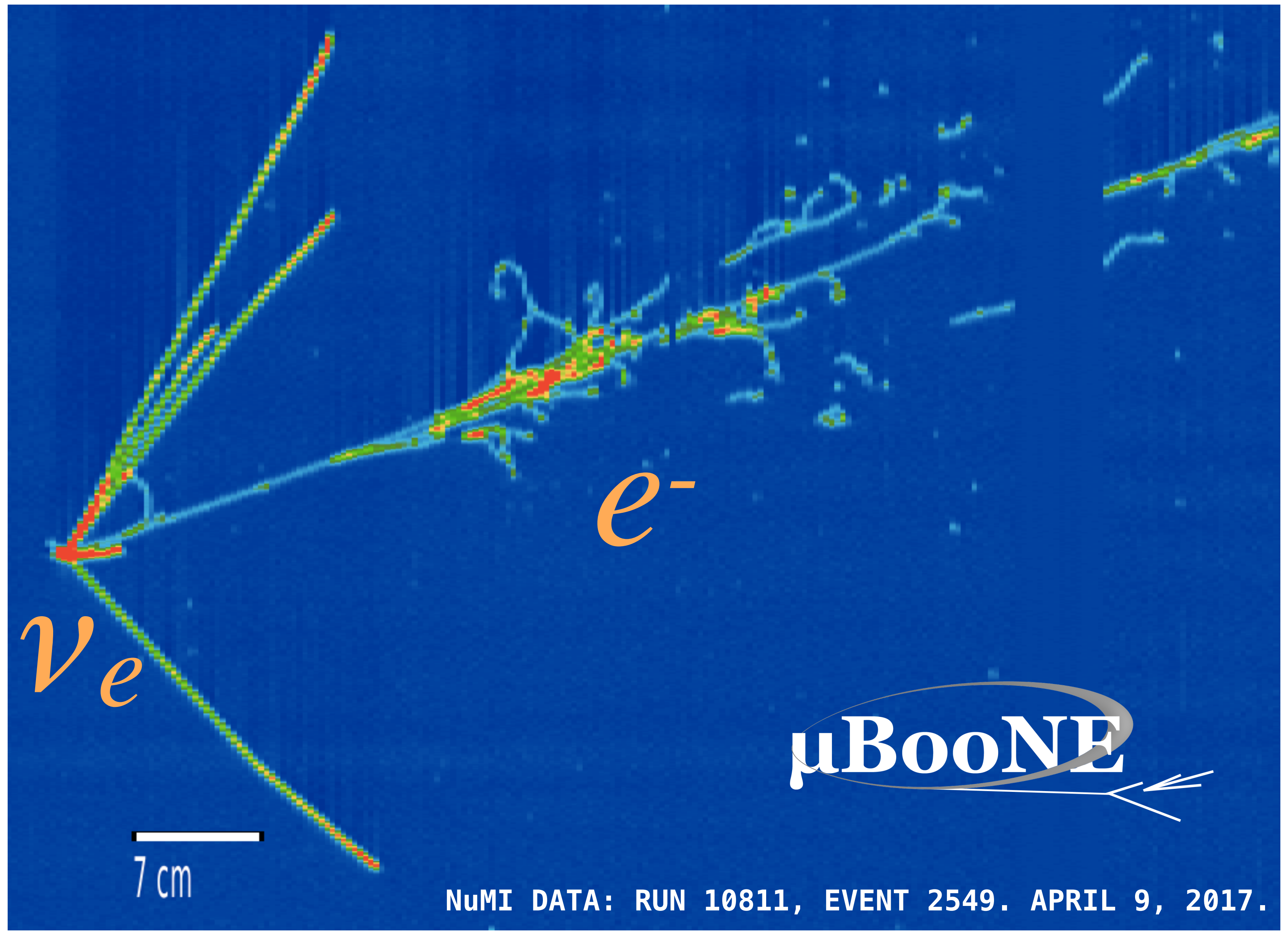

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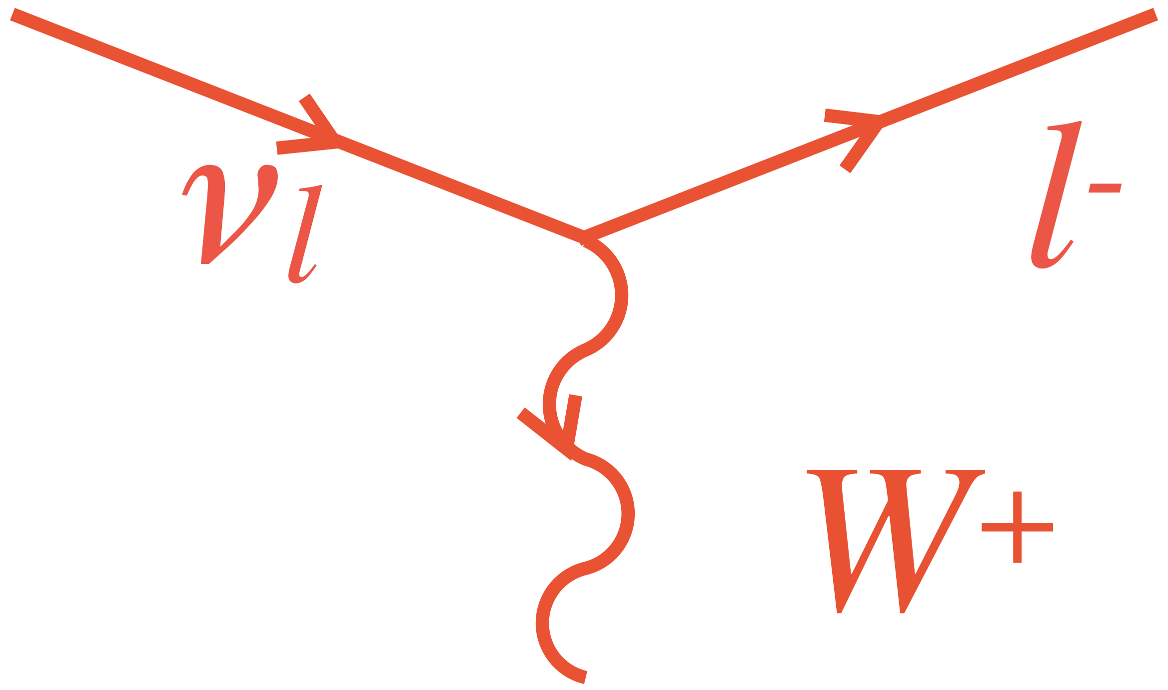

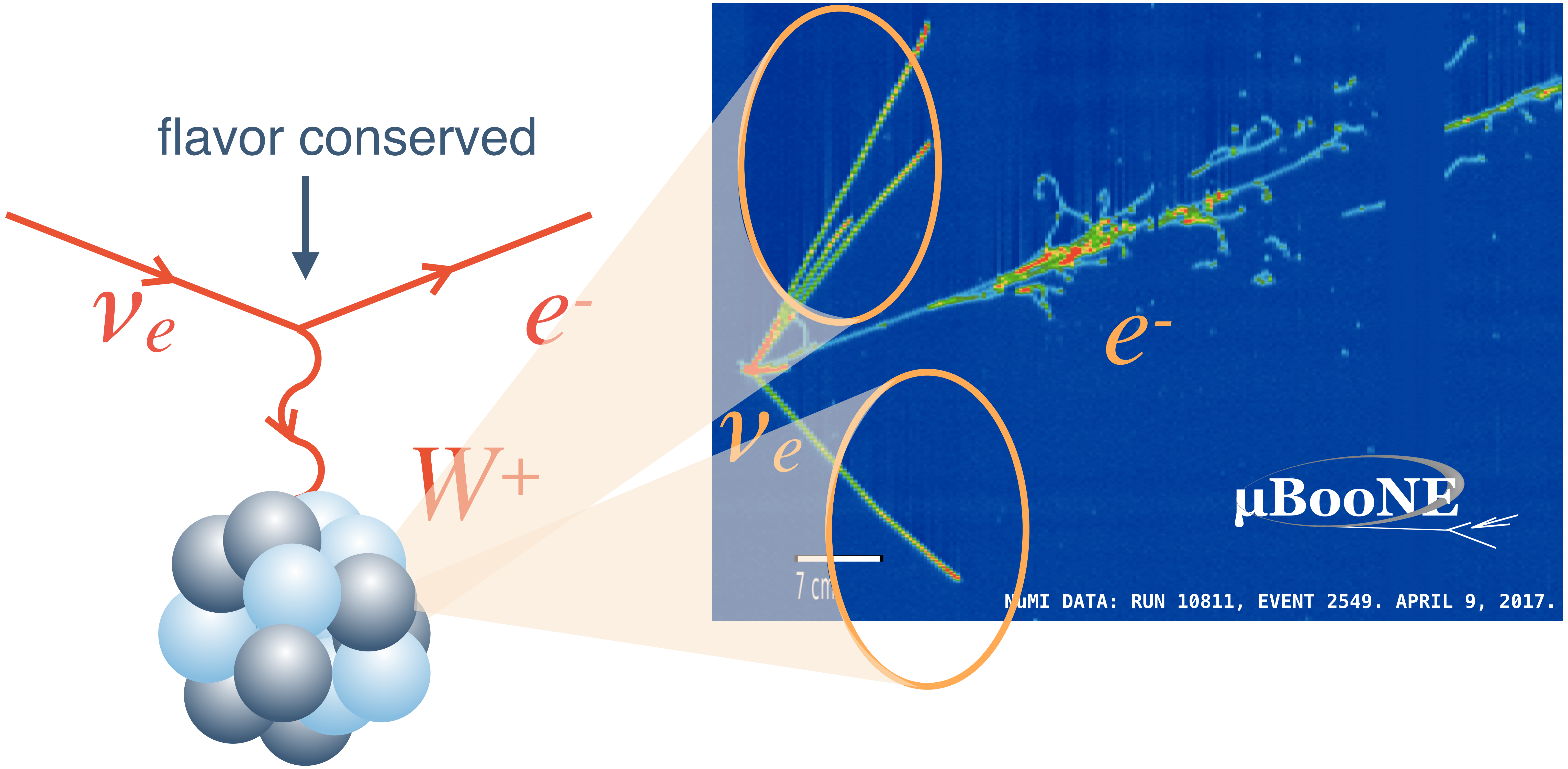

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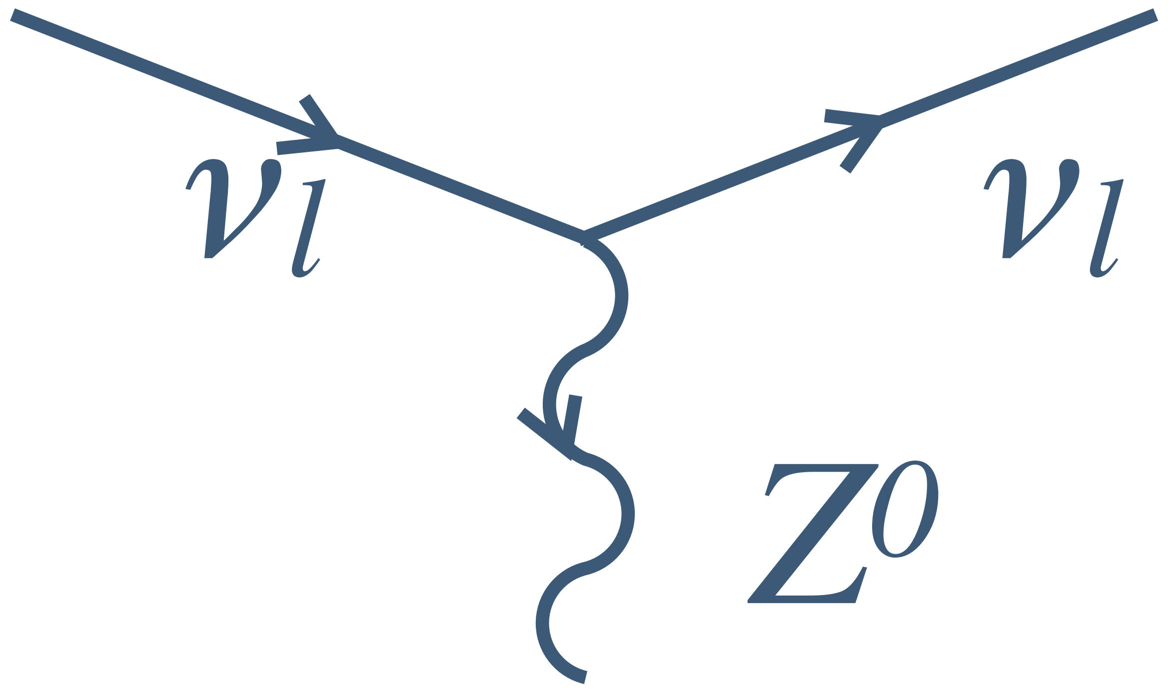
What do we want to know about it?

Particle ID
(flavor)

Momentum

Neutral-current interaction



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What do we want to know about it?

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Momentum

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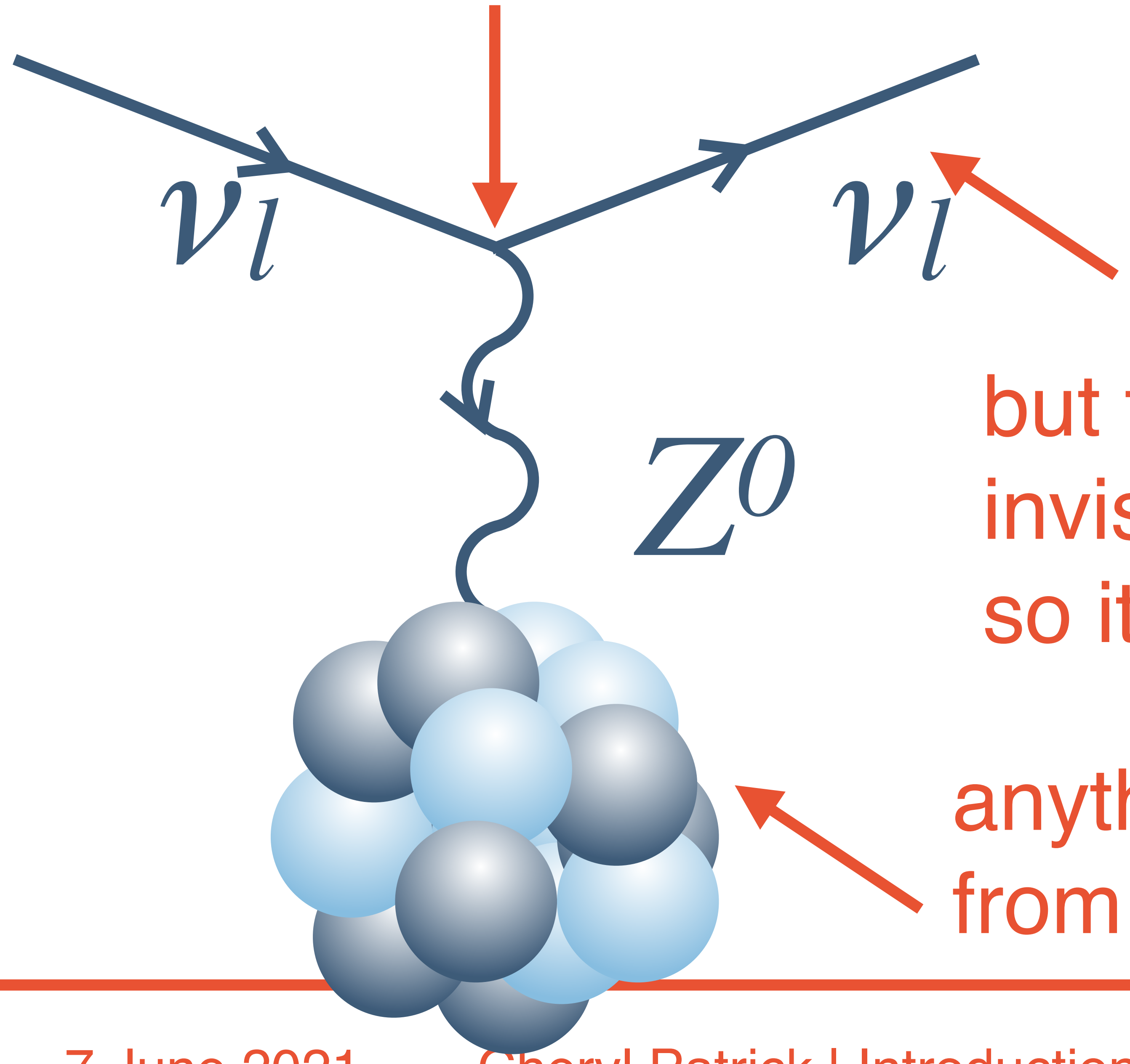


flavor still conserved

but this is
invisible,
so it doesn't help

anything we see comes
from the nucleus

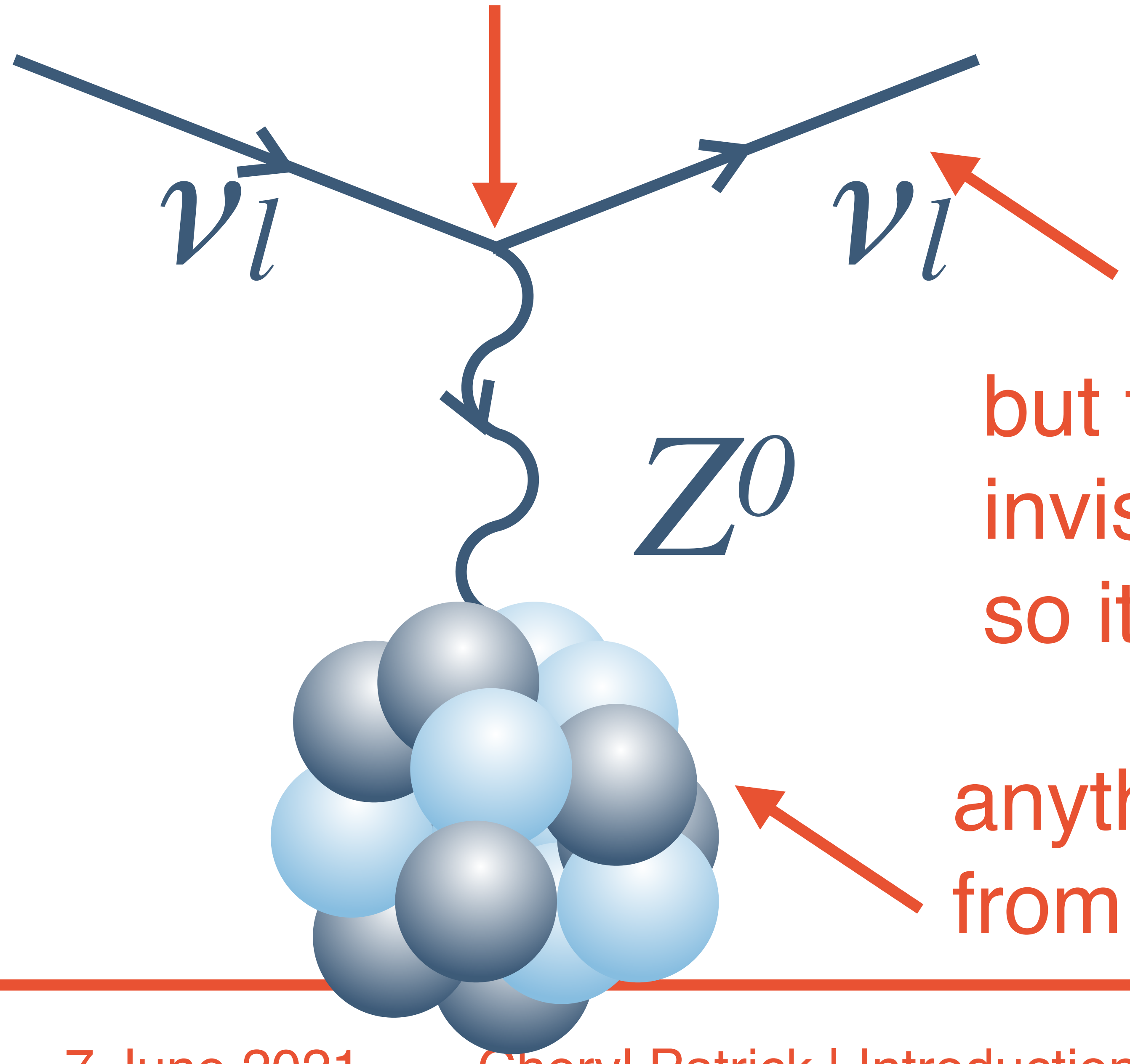
We can detect a neutrino… if it interacts!

What do we want to know about it?

Particle ID (flavor)

Momentum

Neutral-current interaction



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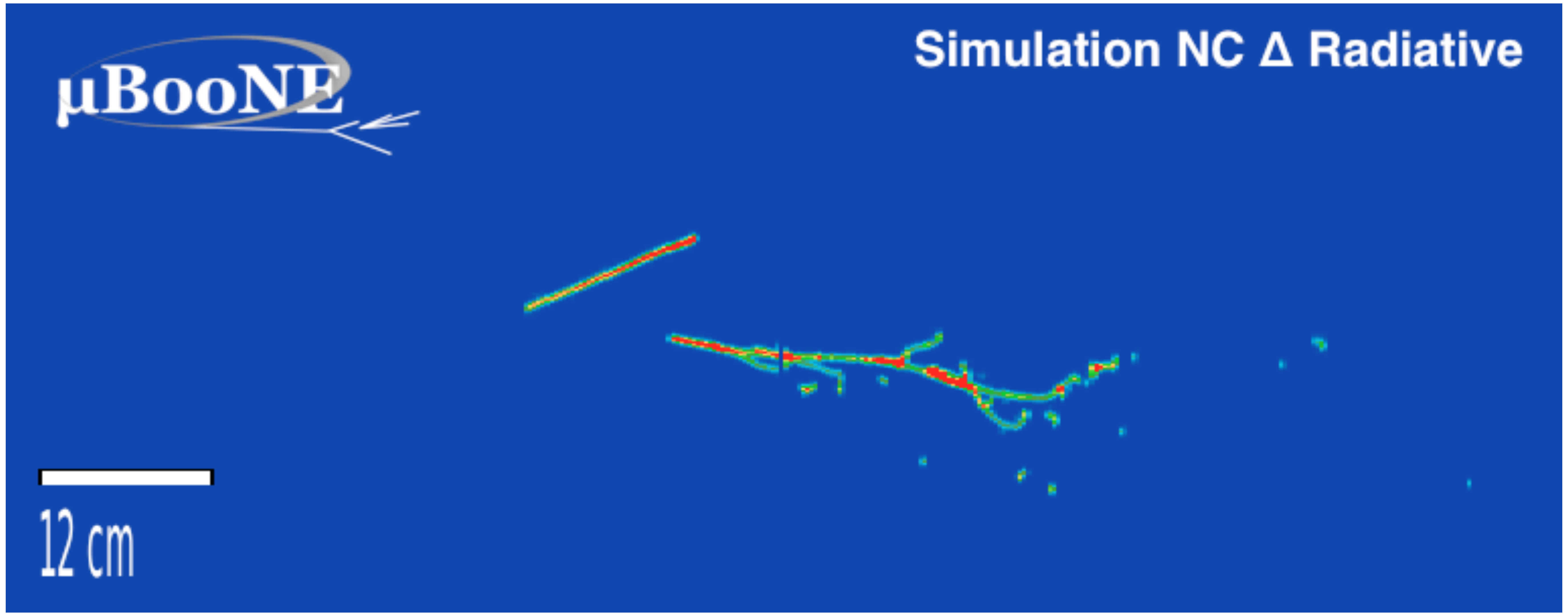

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What do we want to know about it?

Particle ID (flavor)

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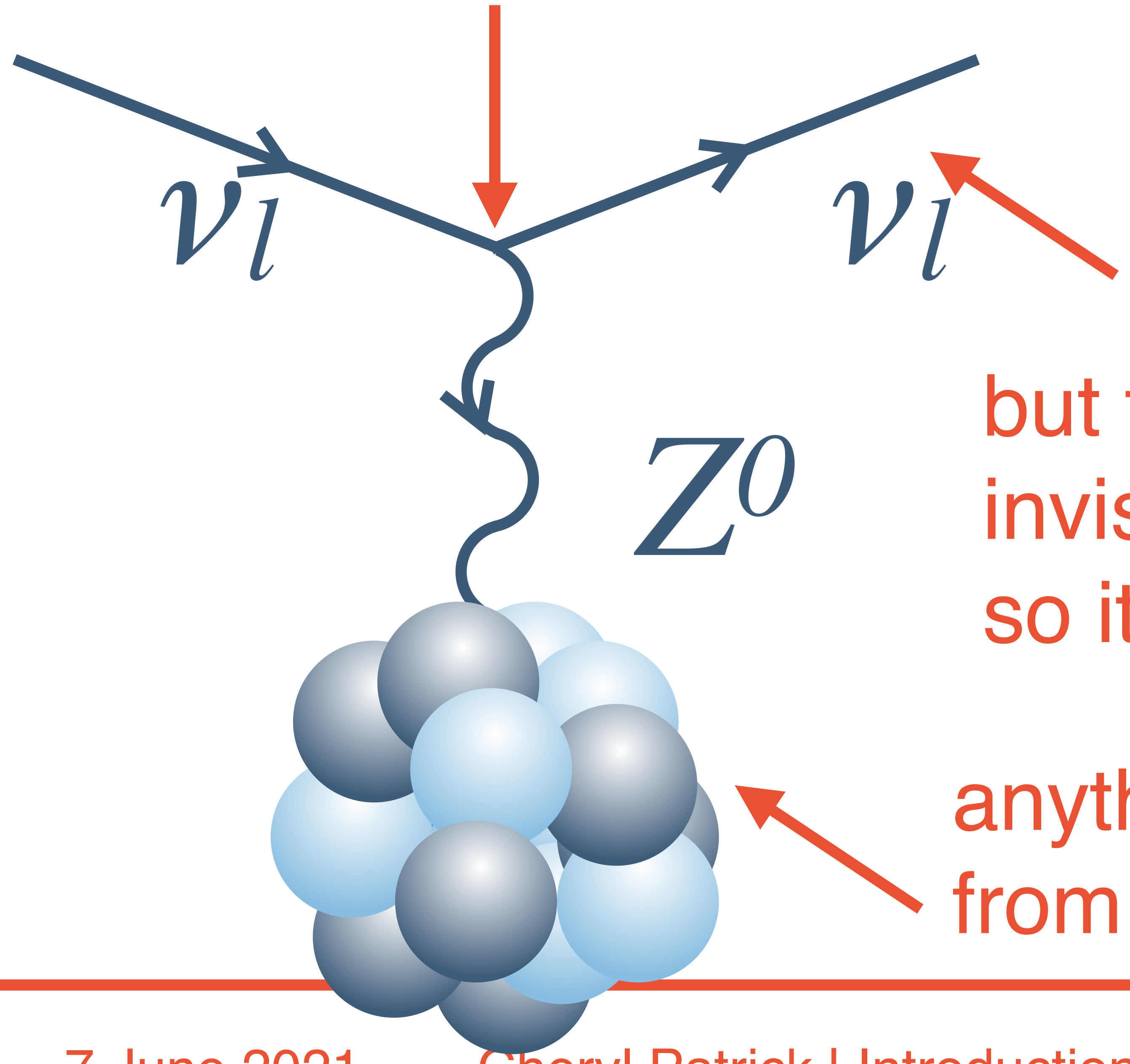

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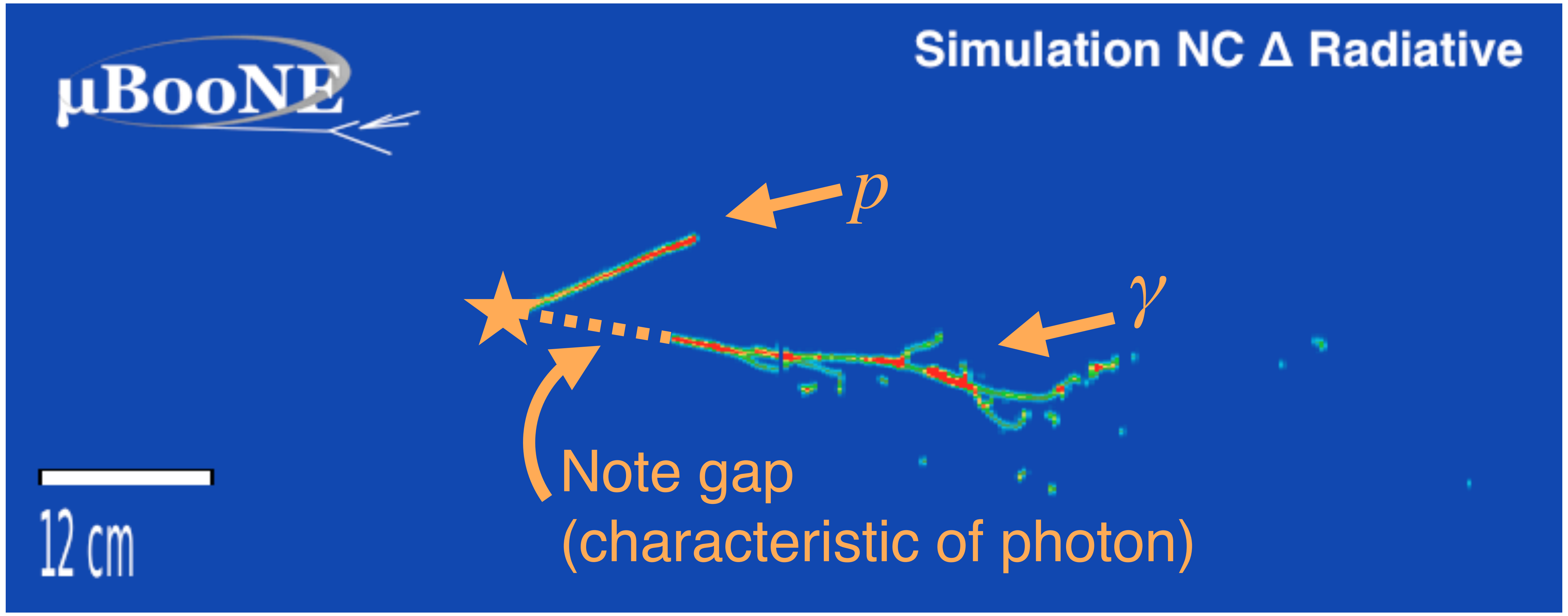
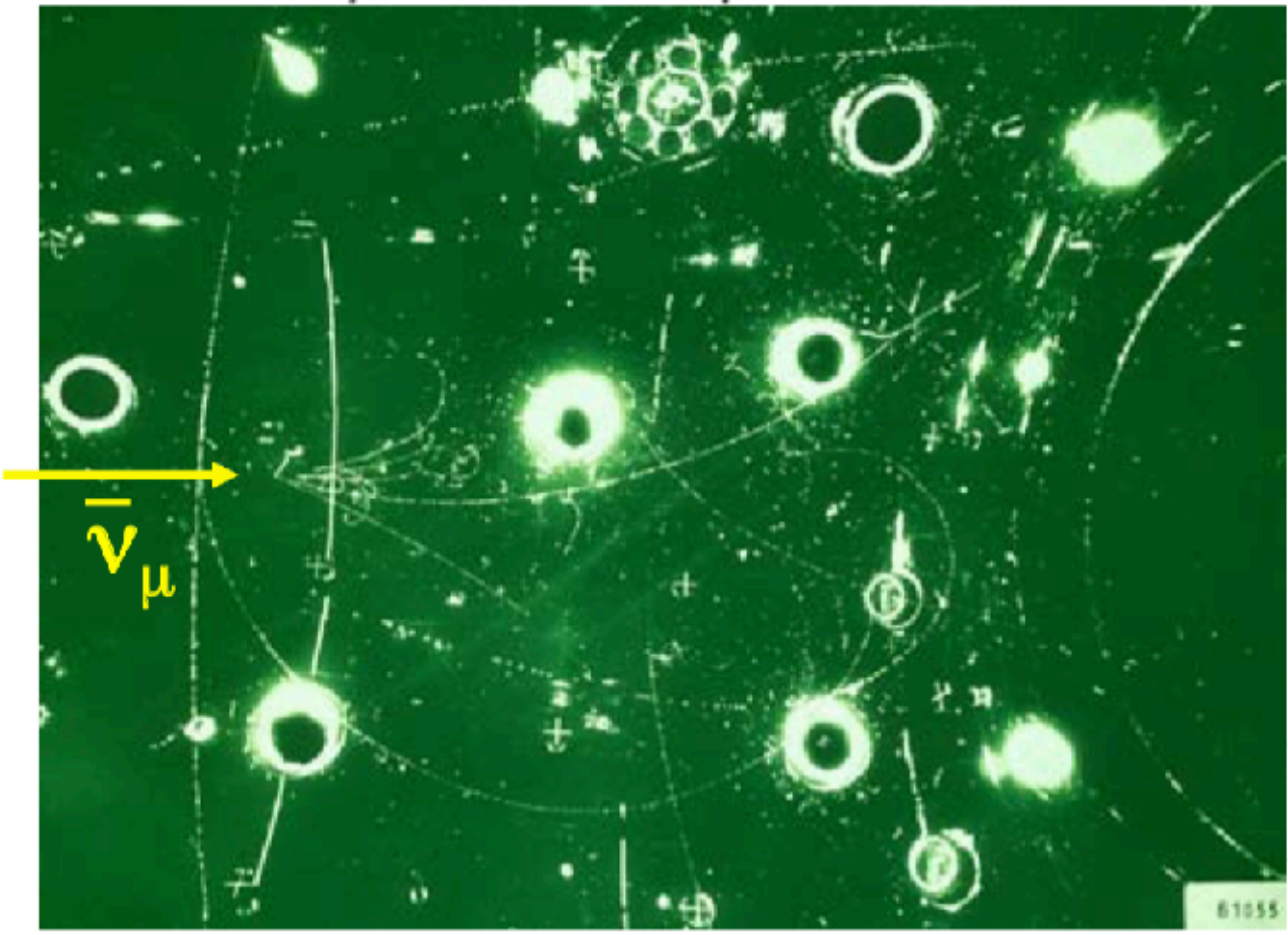


Note gap (characteristic of photon)

This was how the Z boson was discovered!

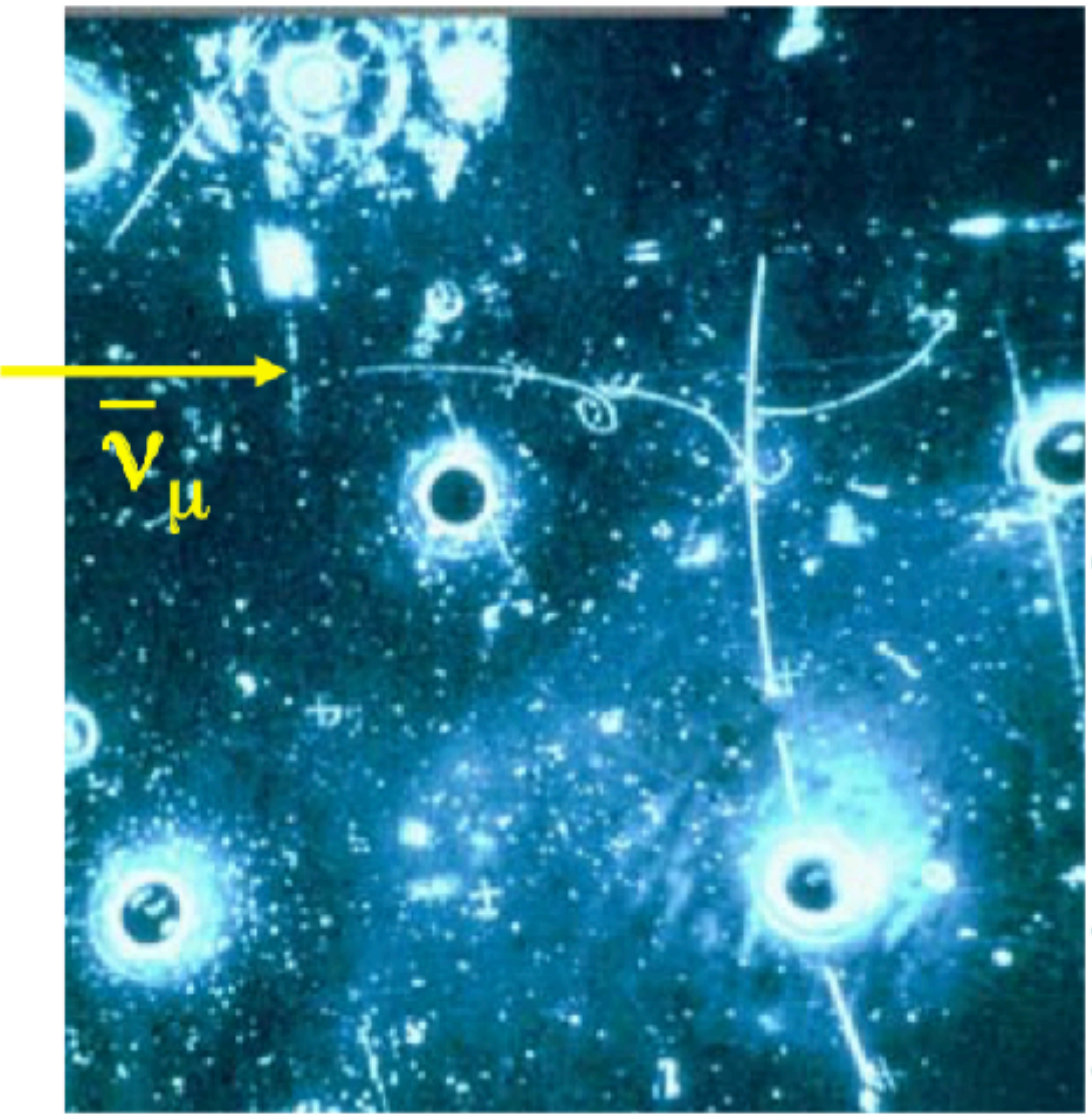
$$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + \text{hadrons}$$



F.J. Hasert et al., Phys. Lett. 46B (1973) 138

From slides by M.A. Thomson

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$



F.J. Hasert et al., Phys. Lett. 46B (1973) 12

Gargamelle bubble chamber, CERN, 1973

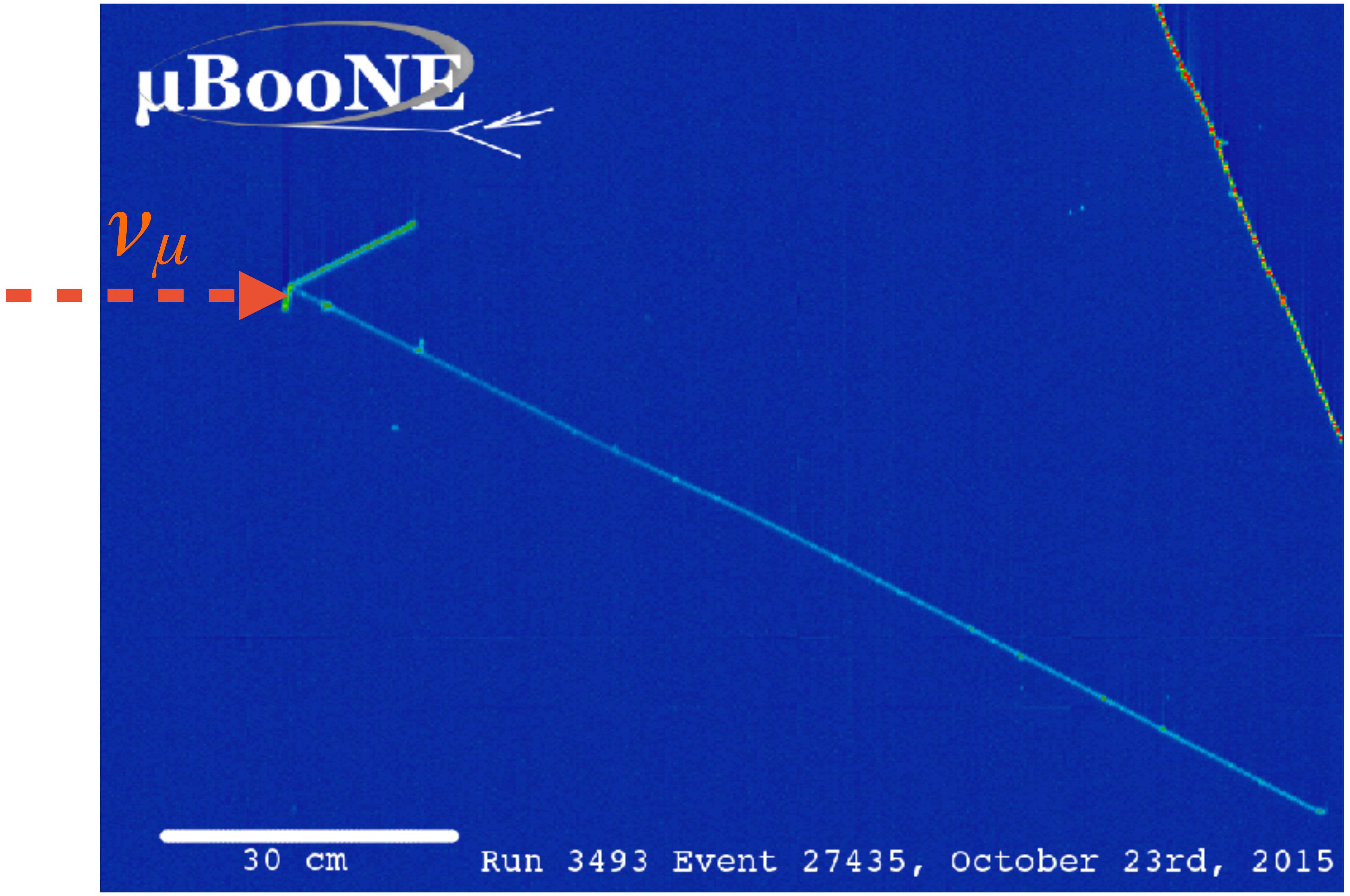
We can detect a neutrino… if it interacts!

What do we want to know about it?

Particle ID

Momentum

= energy, if you know the beam direction



How can we reconstruct the neutrino energy?

We can detect a neutrino… if it interacts!

What do we want to know about it?

Particle ID

Momentum

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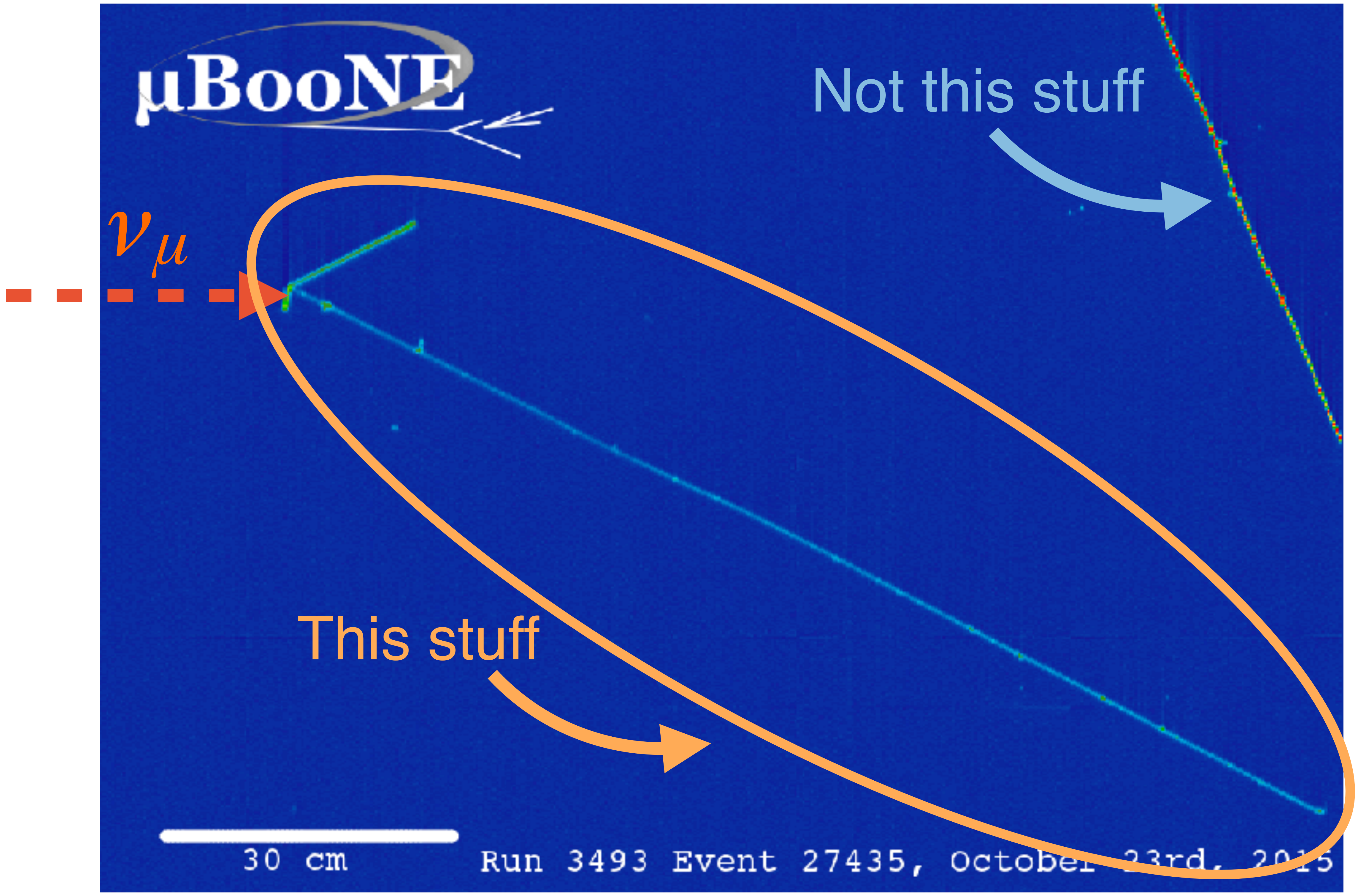

How can we reconstruct the neutrino energy?

Conserve energy

- Sum up energy deposits associated with the interaction: that gives you the final-state kinetic energy

We can detect a neutrino… if it interacts!

What do we want to know about it?


Particle ID

Momentum

= energy, if you know
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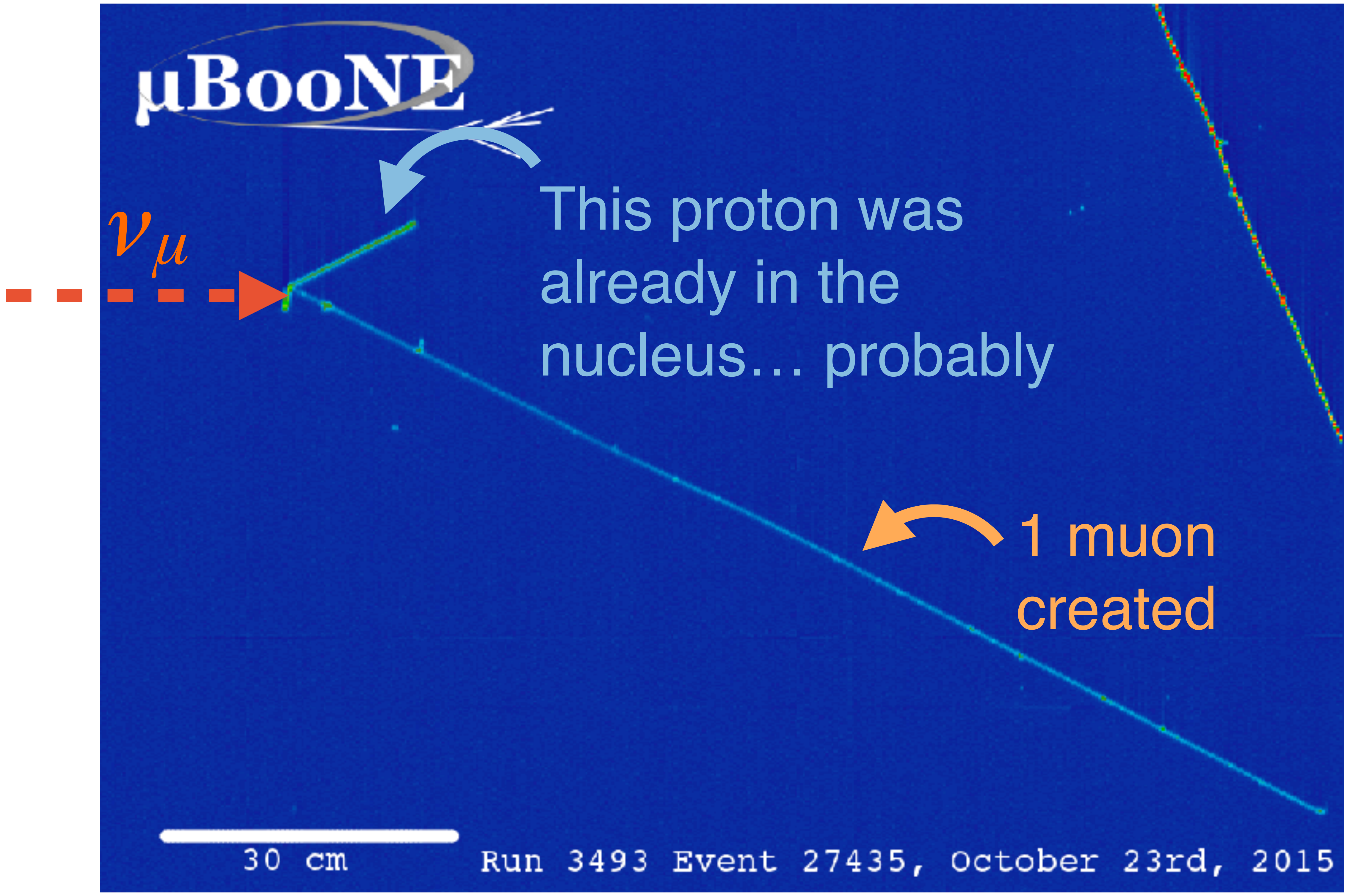

This proton was already in the nucleus… probably

1 muon created

How can we reconstruct the neutrino energy?


Conserve energy

- Sum up energy deposits associated with the interaction: that gives you the final-state kinetic energy
- Add the masses of any particles created

We can detect a neutrino… if it interacts!

What do we want to know about it?

Particle ID

Momentum

= energy, if you know
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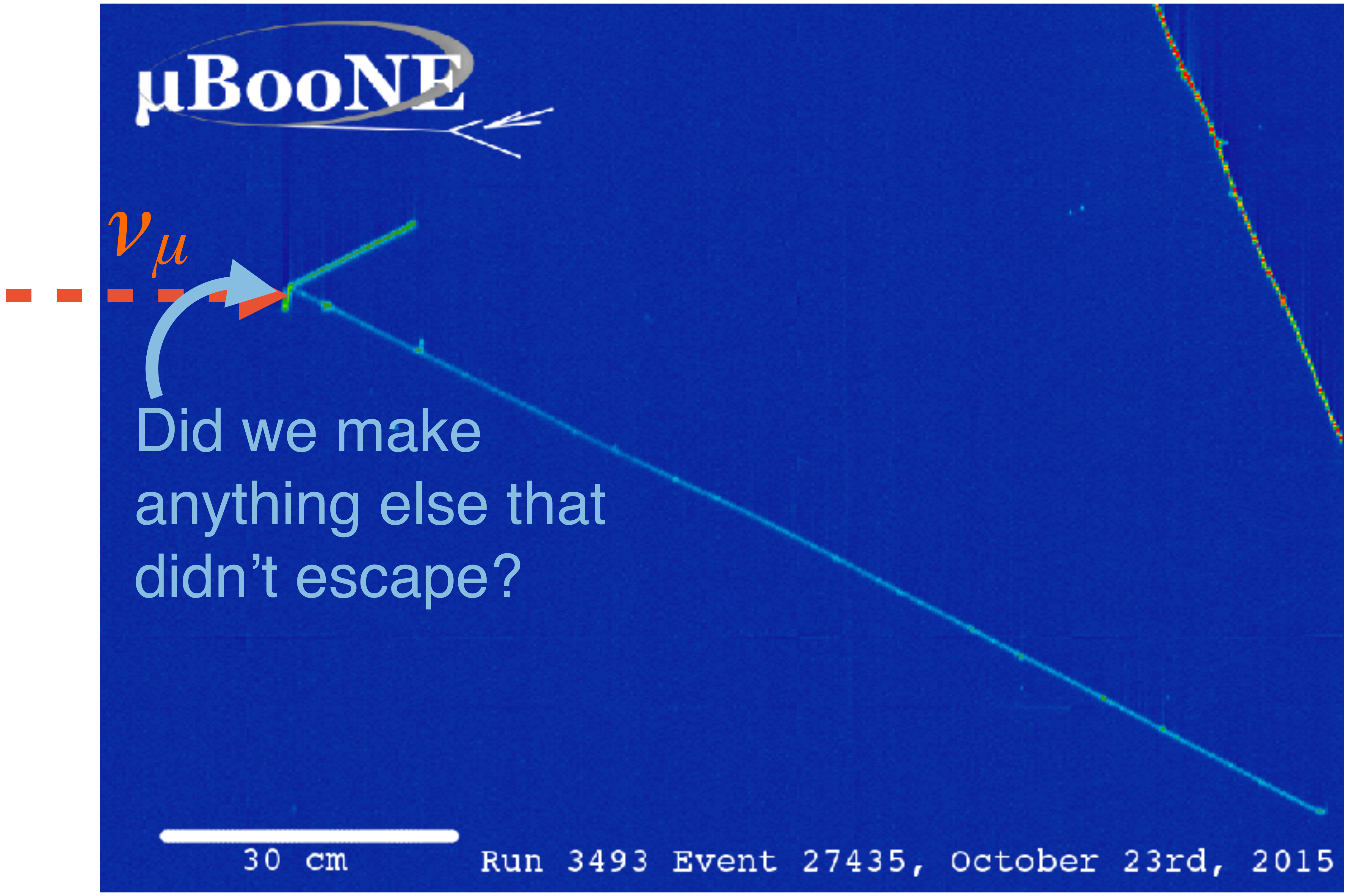


Did we make anything else that didn't escape?

How can we reconstruct the neutrino energy?

Conserve energy

- Sum up energy deposits associated with the interaction: that gives you the final-state kinetic energy
- Add the masses of any particles created
- Could something have been absorbed by the nucleus?
- Not all particles are detectable (e.g. neutral particles)

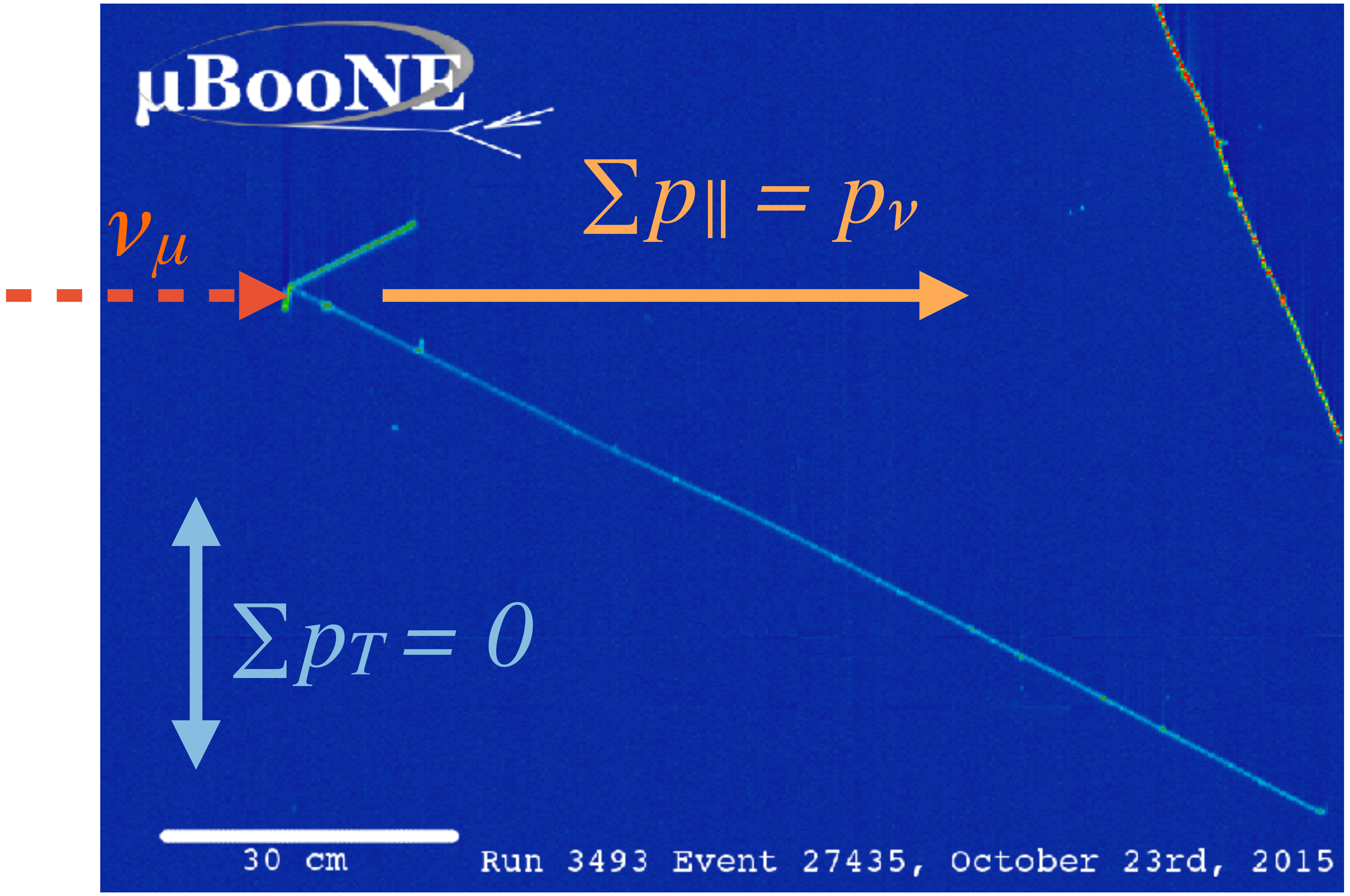
We can detect a neutrino… if it interacts!

What do we want to know about it?

Particle ID

Momentum

= energy, if you know the beam direction



How can we reconstruct the neutrino energy?

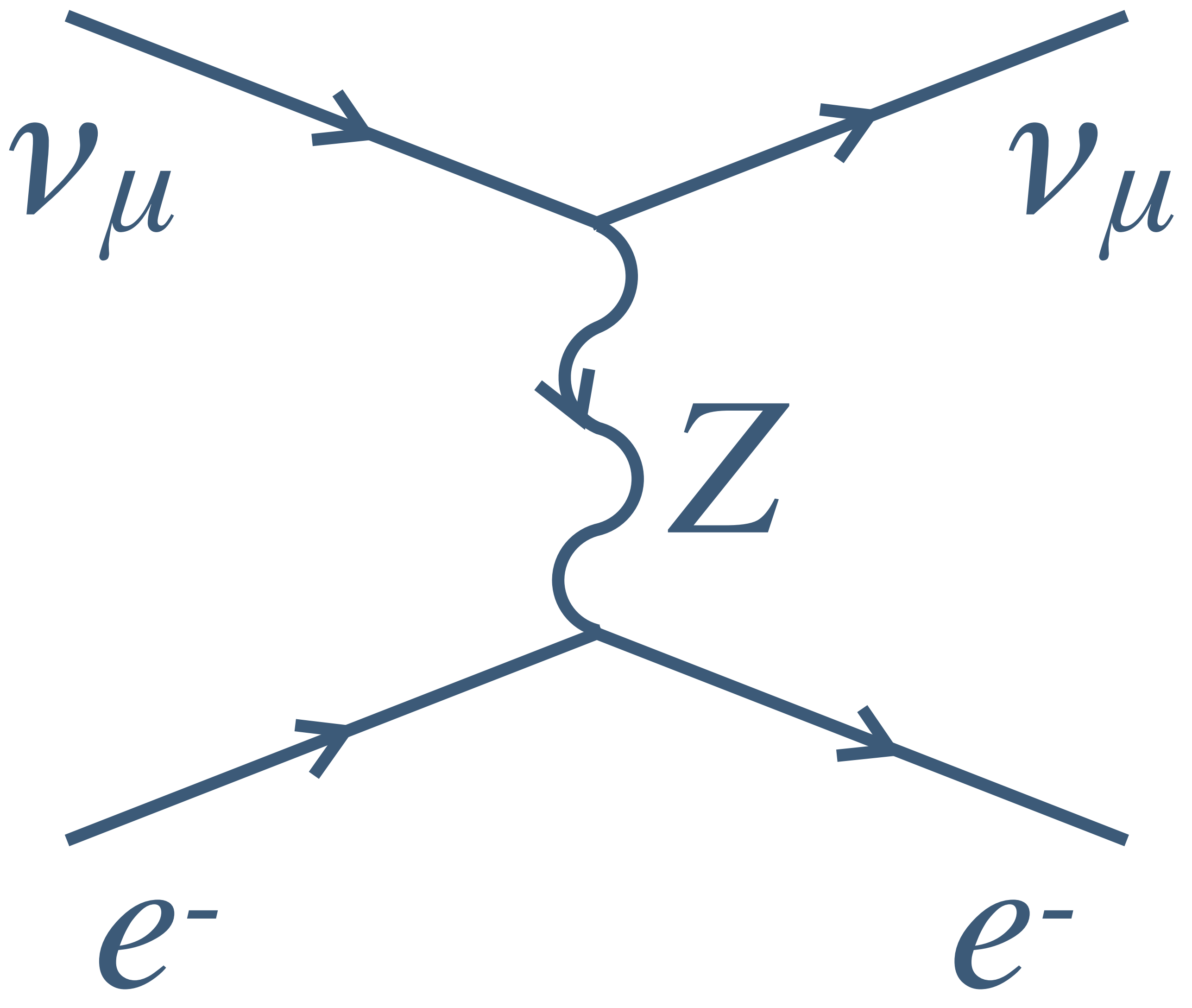
Conserve energy

Conserve momentum

Look parallel ($p_\parallel$) and transverse (p_T) to the beam for an extra degree of freedom…

Neutrino-electron elastic scattering

Exercise 4

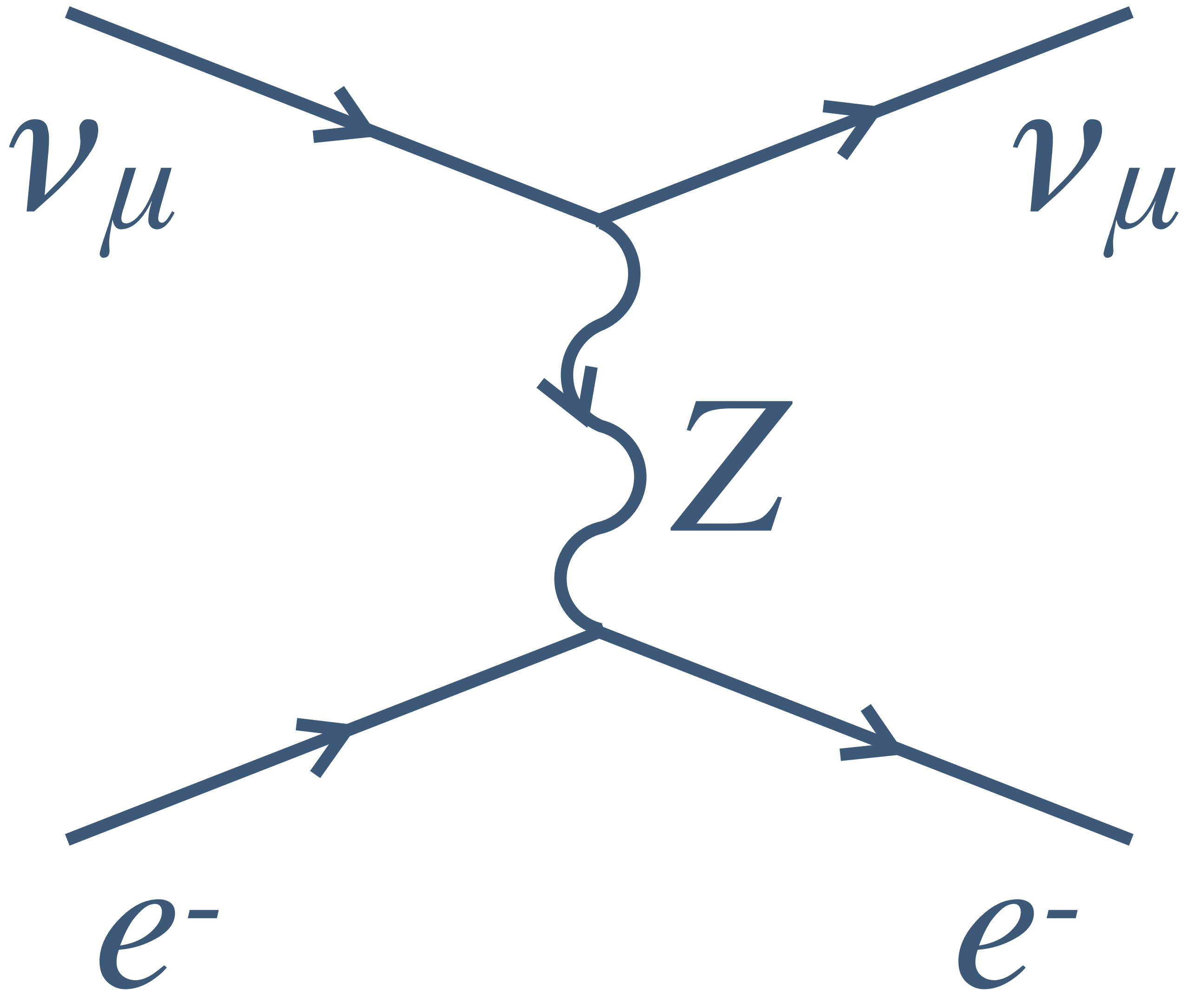


What's the equivalent for ν_e - e^- scattering?
Can you find another ν_e - e^- scattering with he same final state as the first one you found?

- Electrons are **fundamental** particles
- Weak scattering is well understood
- Calculate neutrino energy from electron kinematics: good way to study **neutrino flux** *e.g. Phys. Rev. D 93, 112007 (2016)*

Neutrino-electron elastic scattering

Exercise 4



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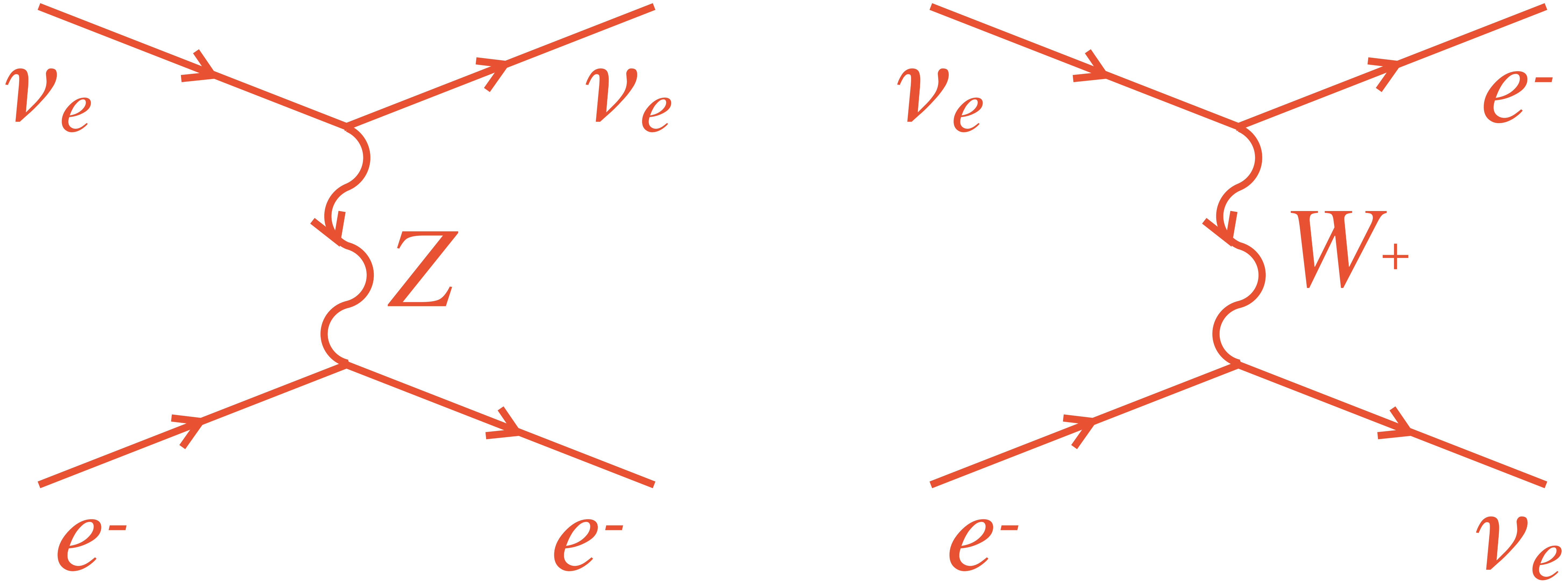

- Electrons are **fundamental** particles
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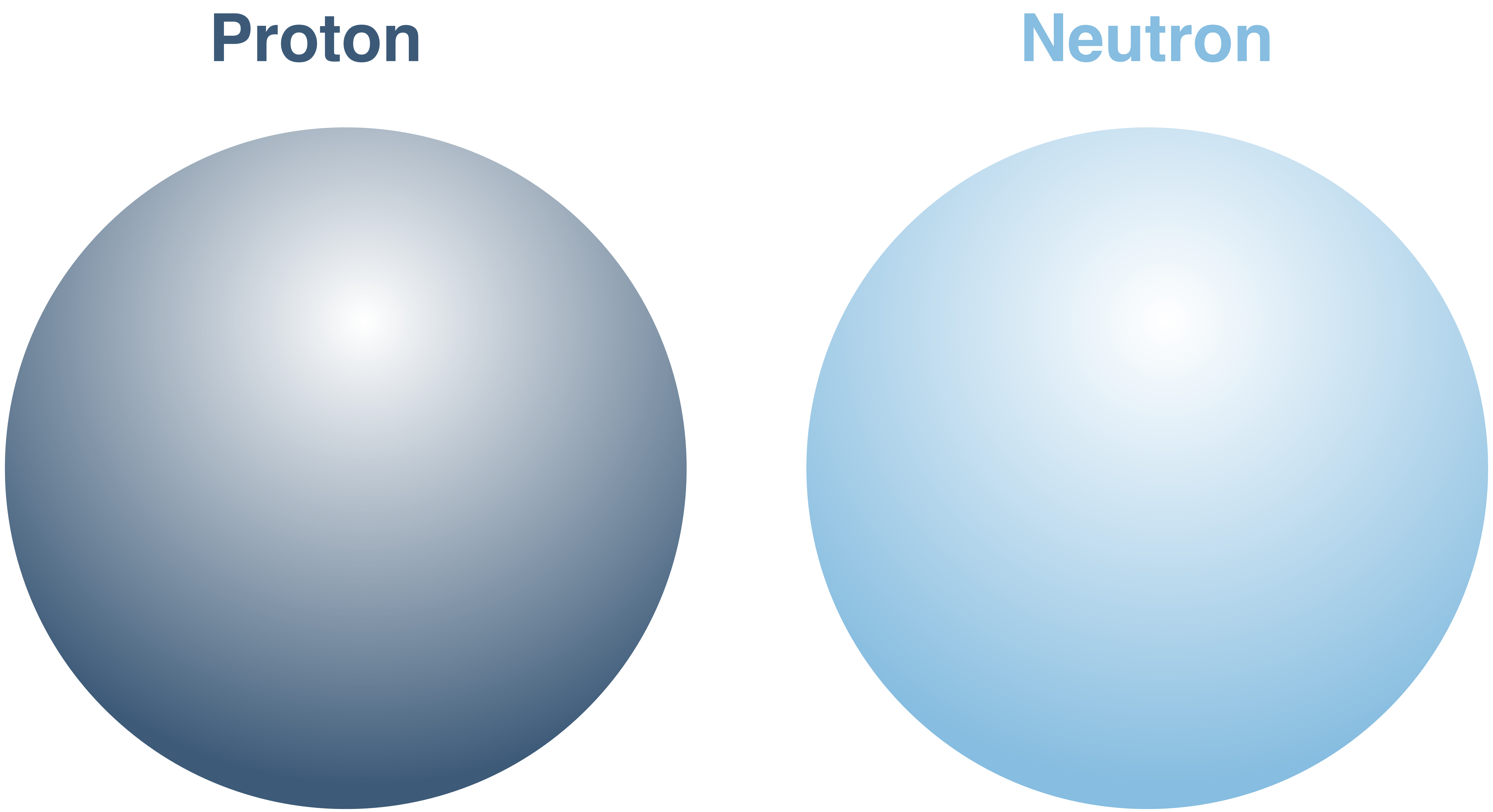
All lepton interactions have the same strengths in the weak interaction (**lepton universality**), but because of **interference** with the CC diagram, the ν_e - e^- cross section is different from the ν_μ - e^-

Nucleons

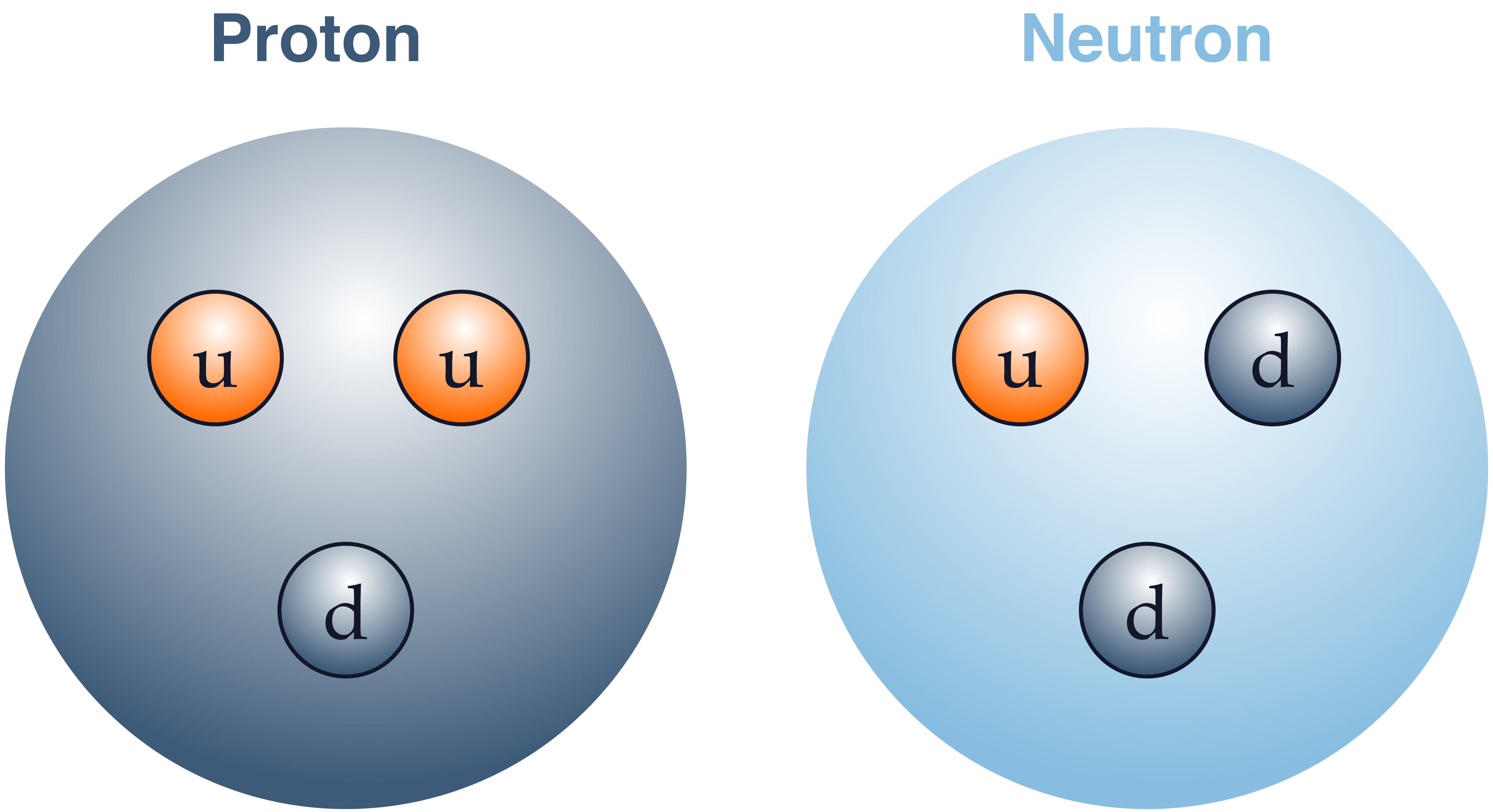
Things get more complicated (and it's only getting worse from here…)



Nucleons are composite particles and contain:

Nucleons

Things get more complicated (and it's only getting worse from here…)



Nucleons are composite particles and contain:

- Three **valence** quarks

Nucleons

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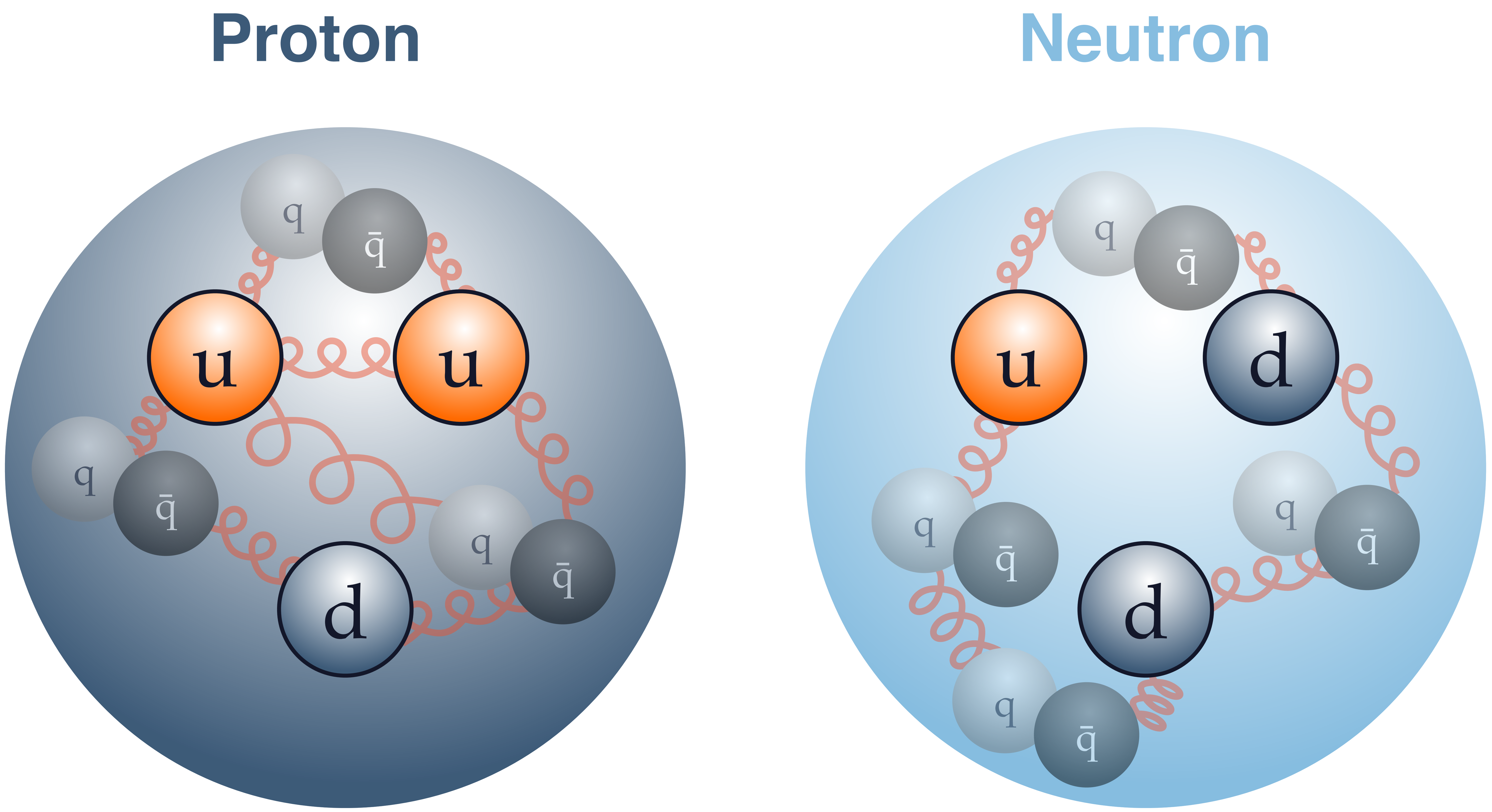

Nucleons are composite particles and contain:

- Three **valence** quarks
- Gluons
- Transient "sea" quarks and antiquarks

Nucleons

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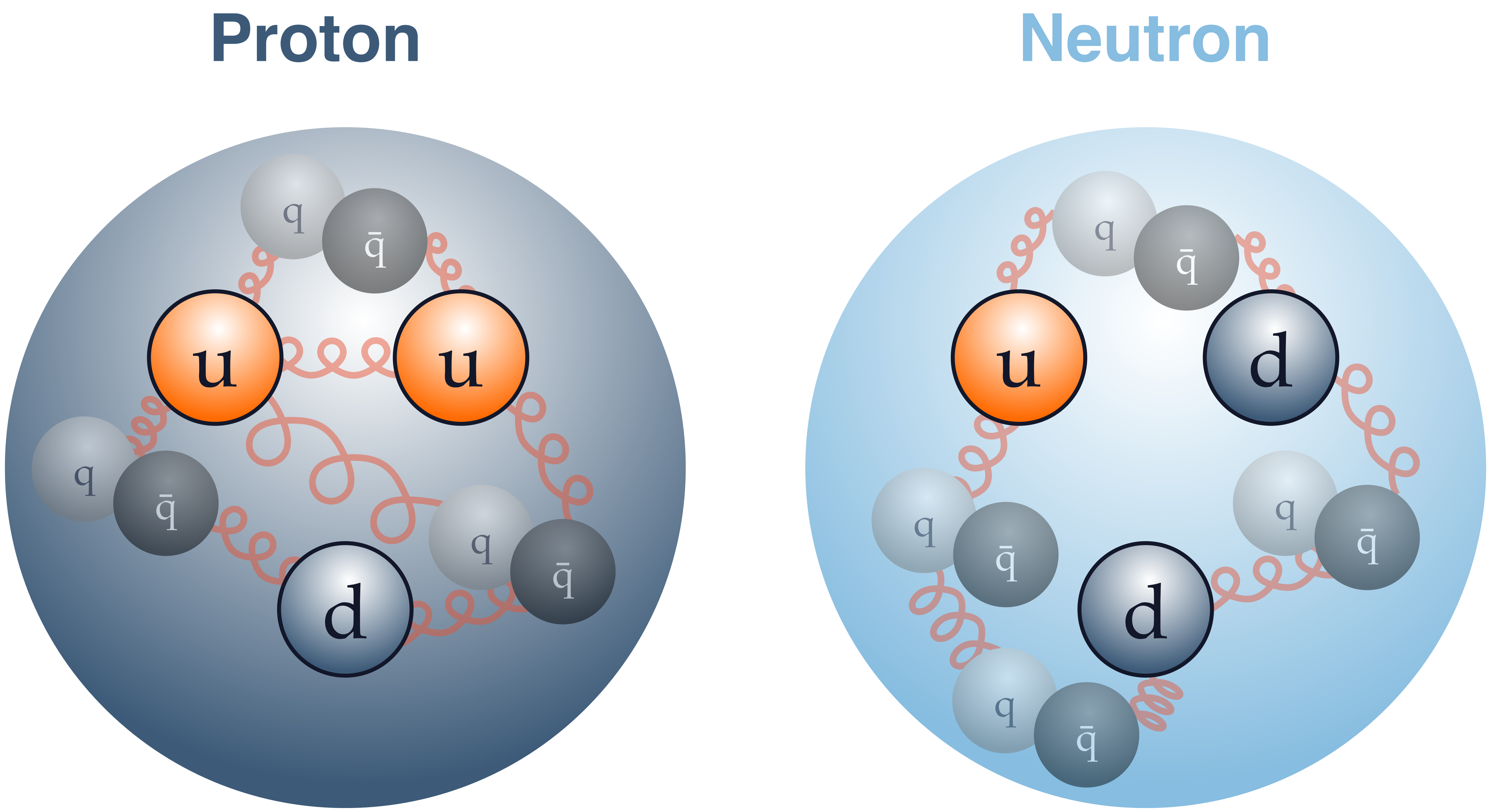

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The quarks can interact weakly (i.e. with neutrinos)

Nucleons

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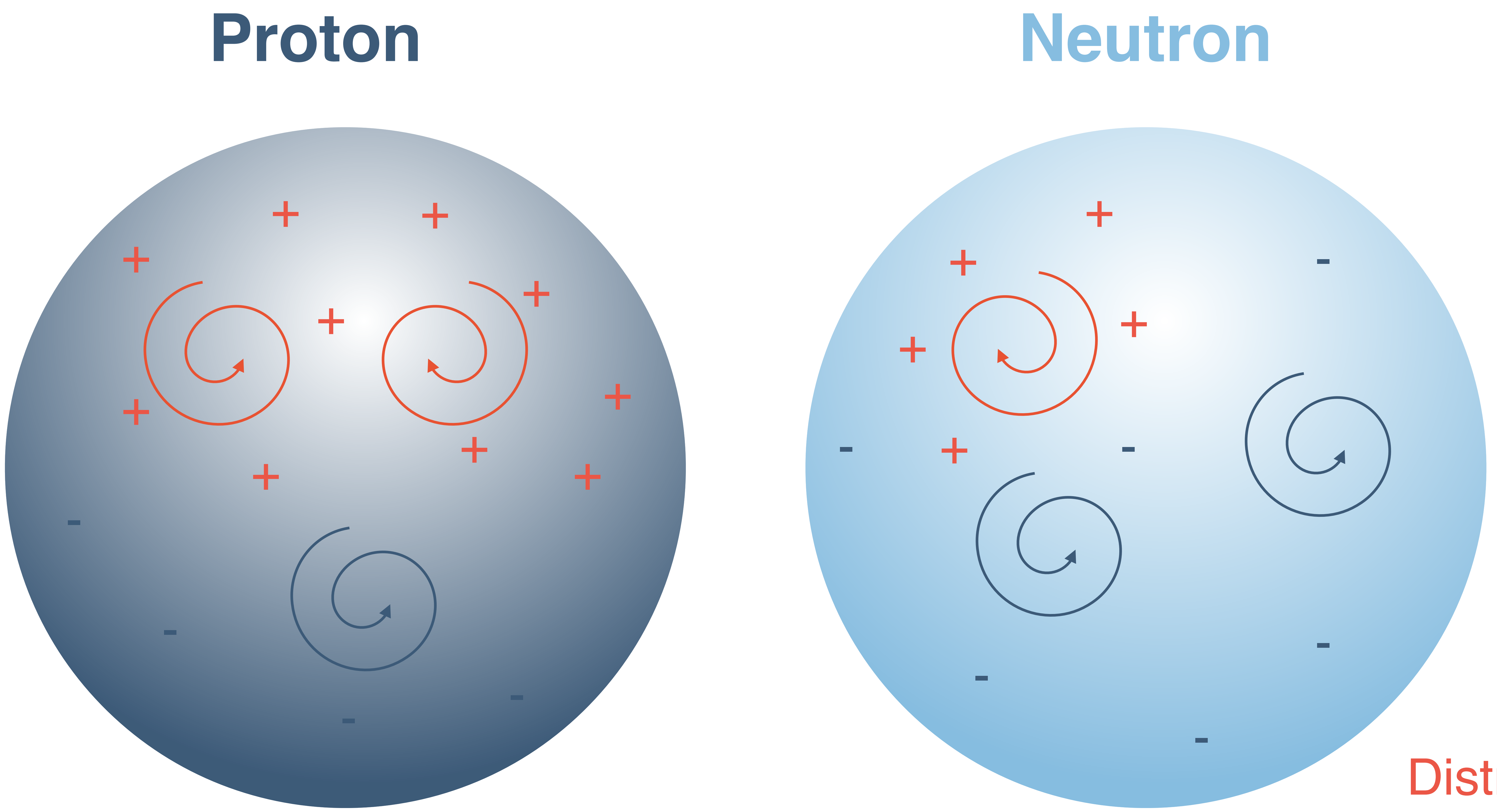


Nucleons are composite particles and contain:

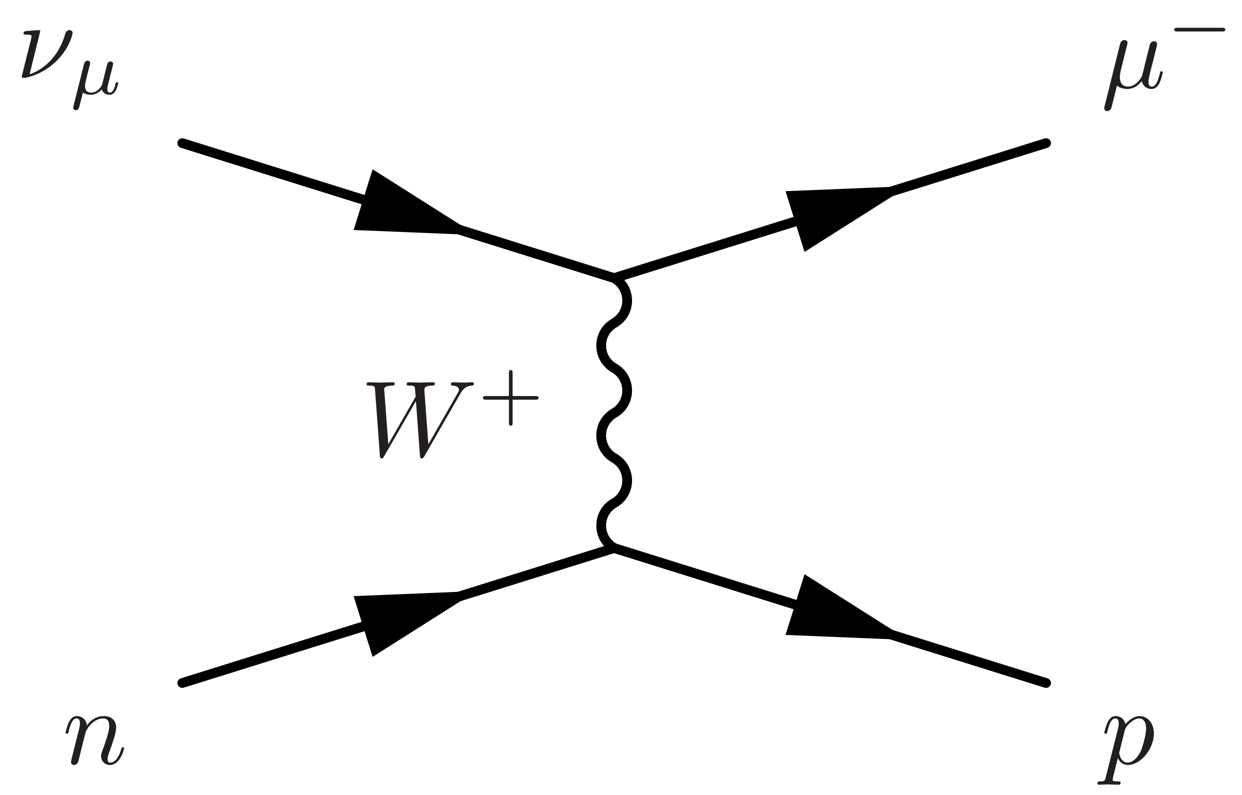
- Three **valence** quarks
- Gluons
- Transient "sea" quarks and antiquarks

The quarks can interact weakly (i.e. with neutrinos)

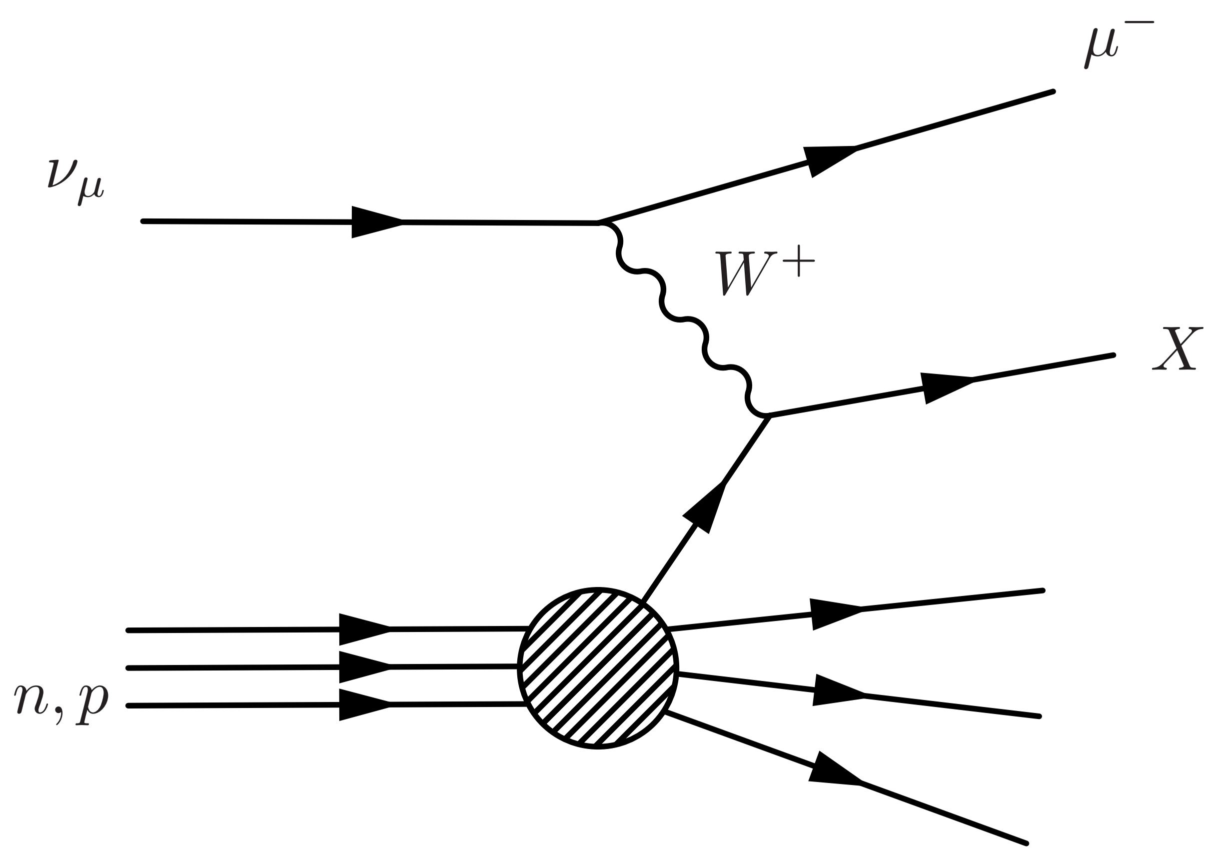
Distribution / motion of quarks gives nucleons an electric and magnetic moment

Three (charged-current) ways neutrinos interact with nucleons

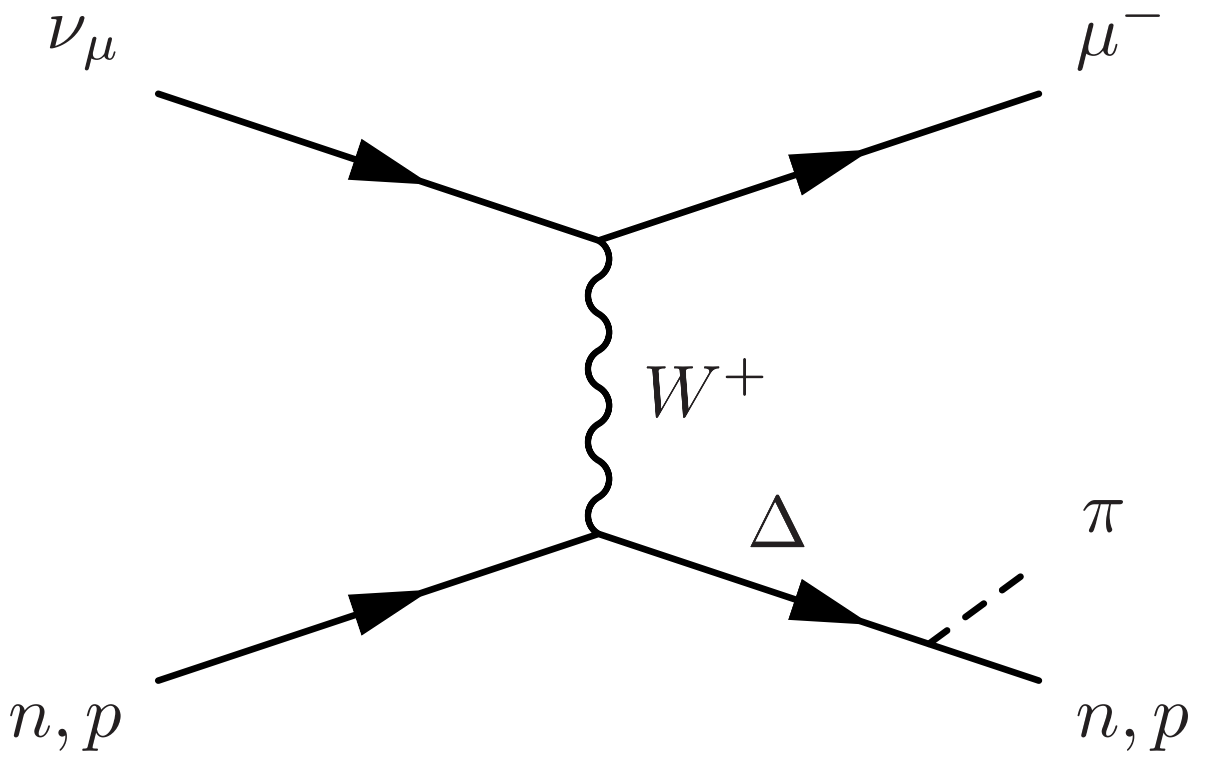
Quasi-elastic scattering



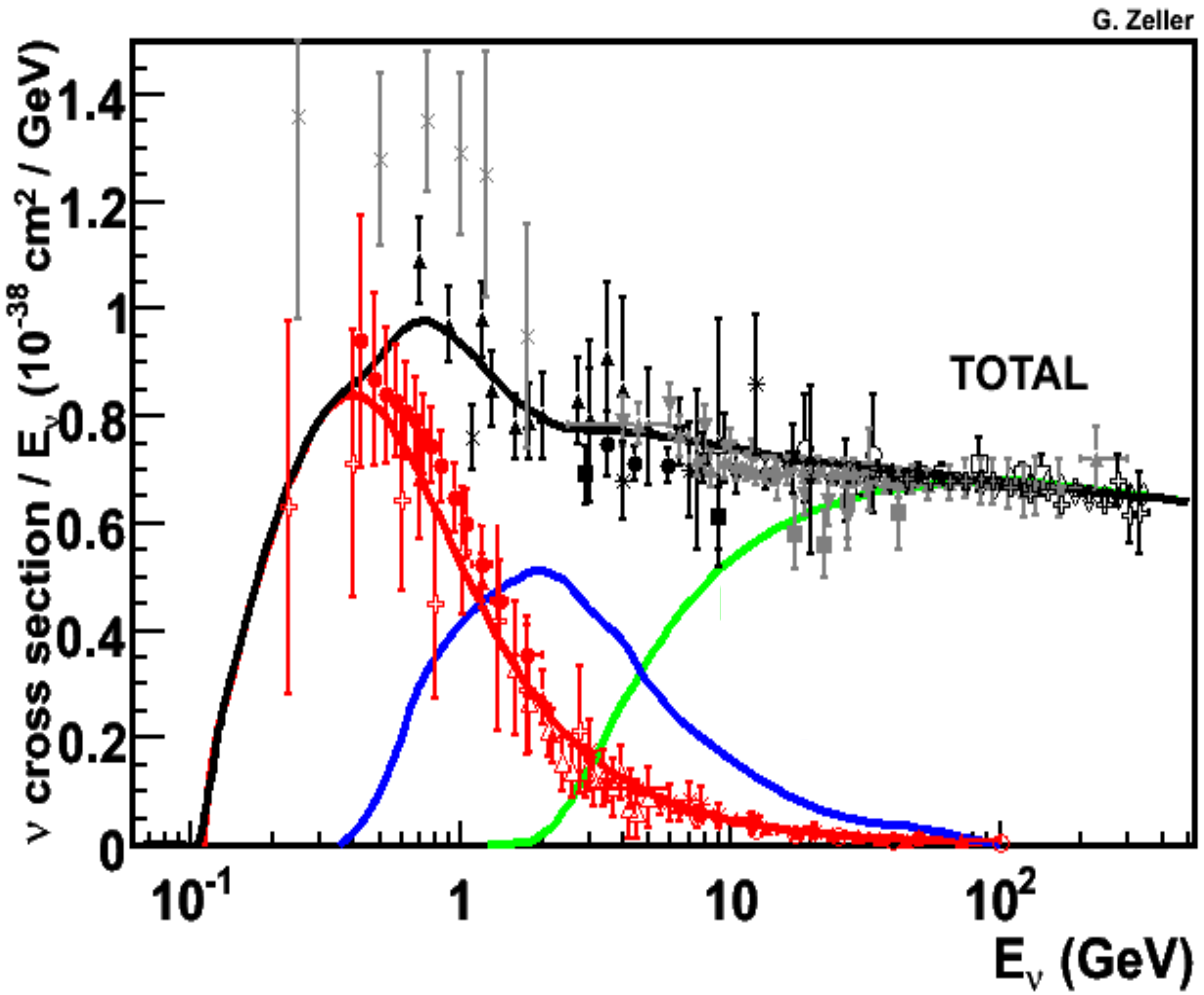
Deep inelastic scattering



Resonant pion production

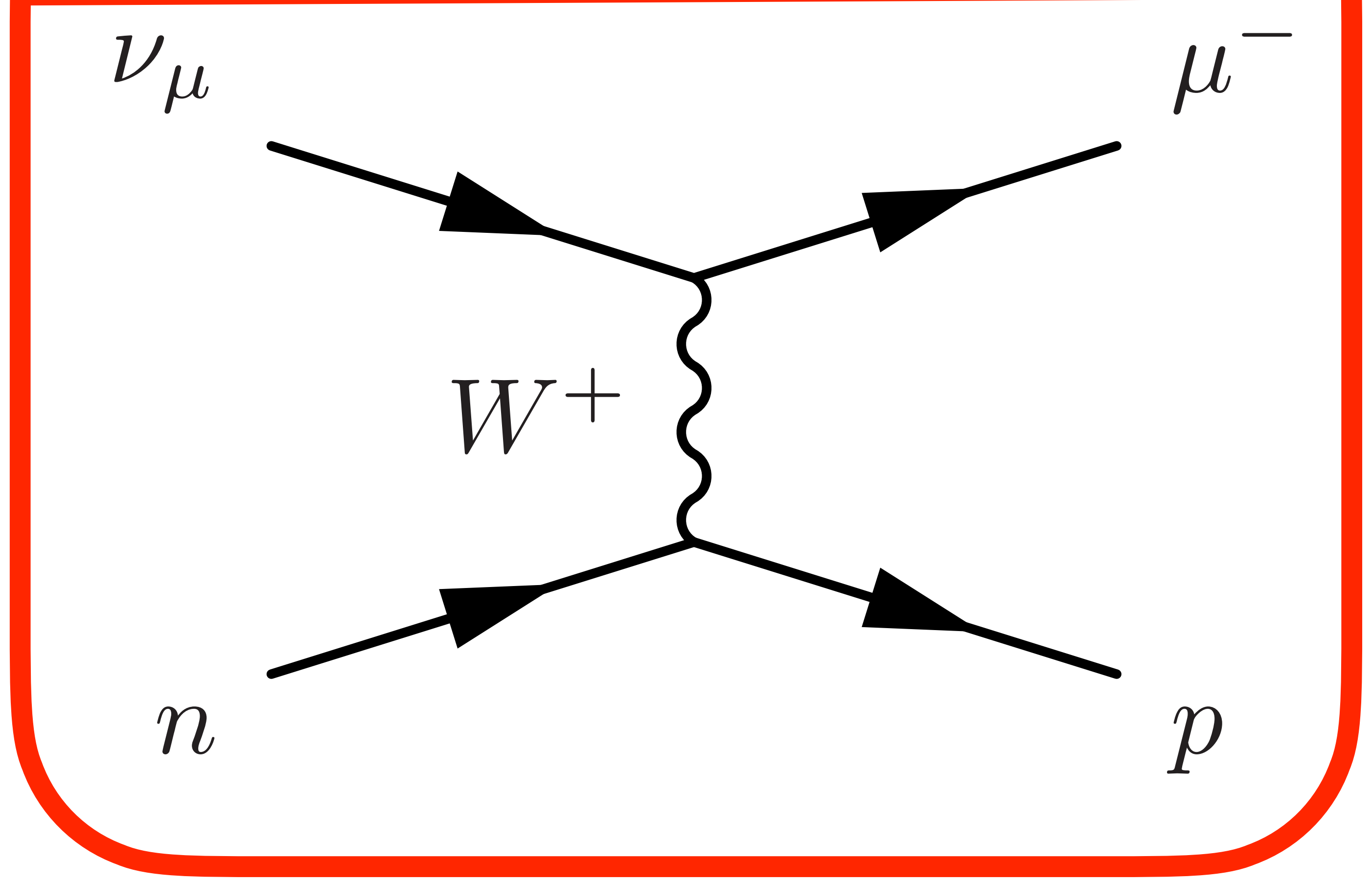


Different scattering modes happen at different energies. What do you think is happening in each of these?
Which do you think correspond to the red, blue, and green lines on the plot?
Hint - why does each curve have a low cut-off?



Three (charged-current) ways neutrinos interact with nucleons

Quasi-elastic scattering



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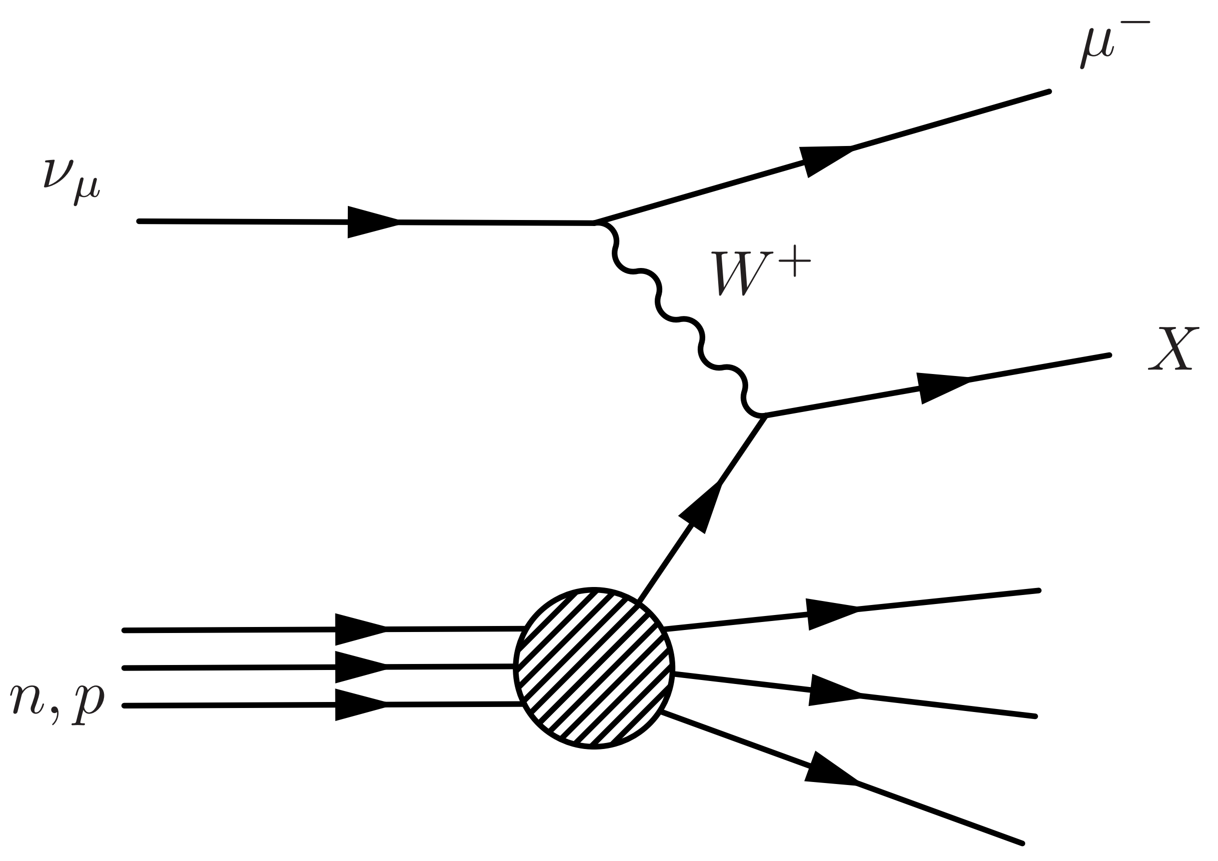

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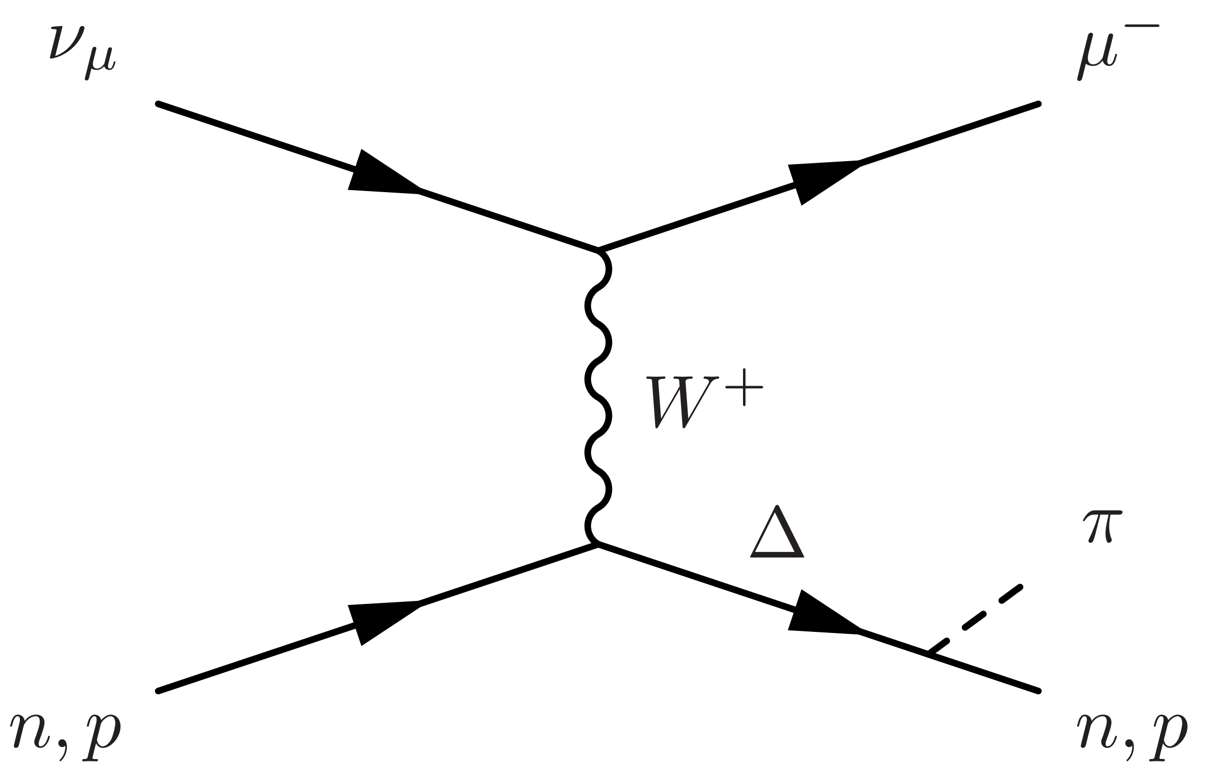

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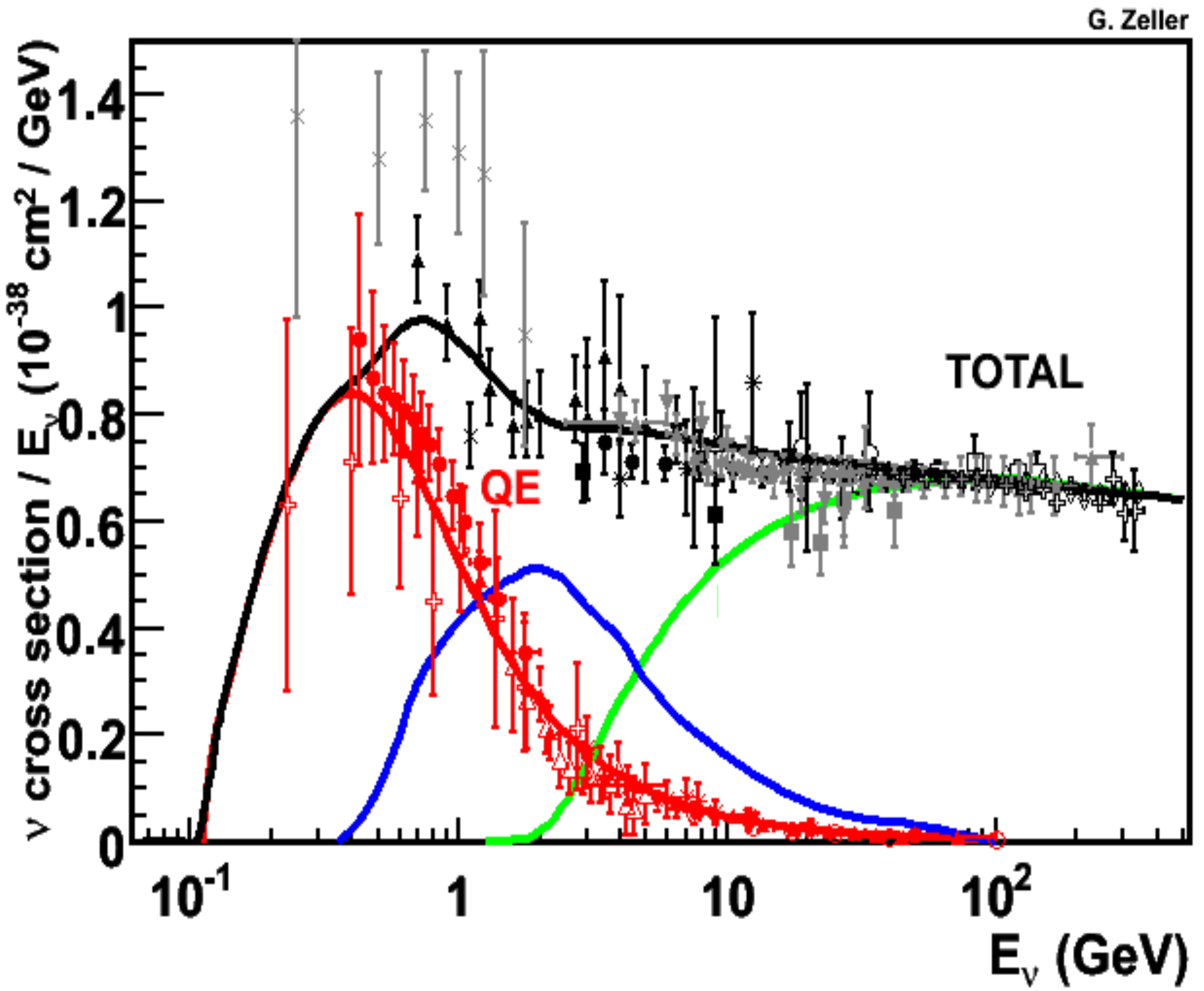

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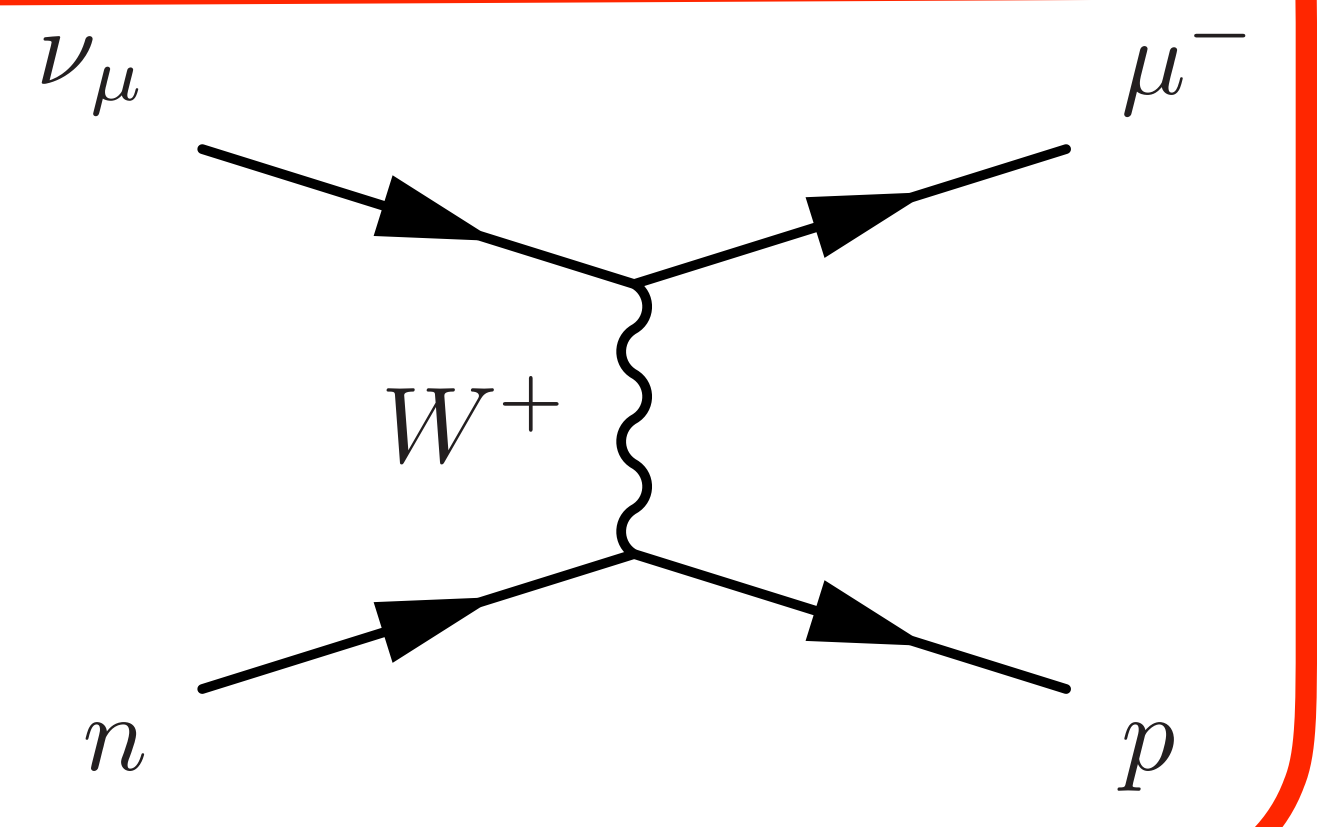

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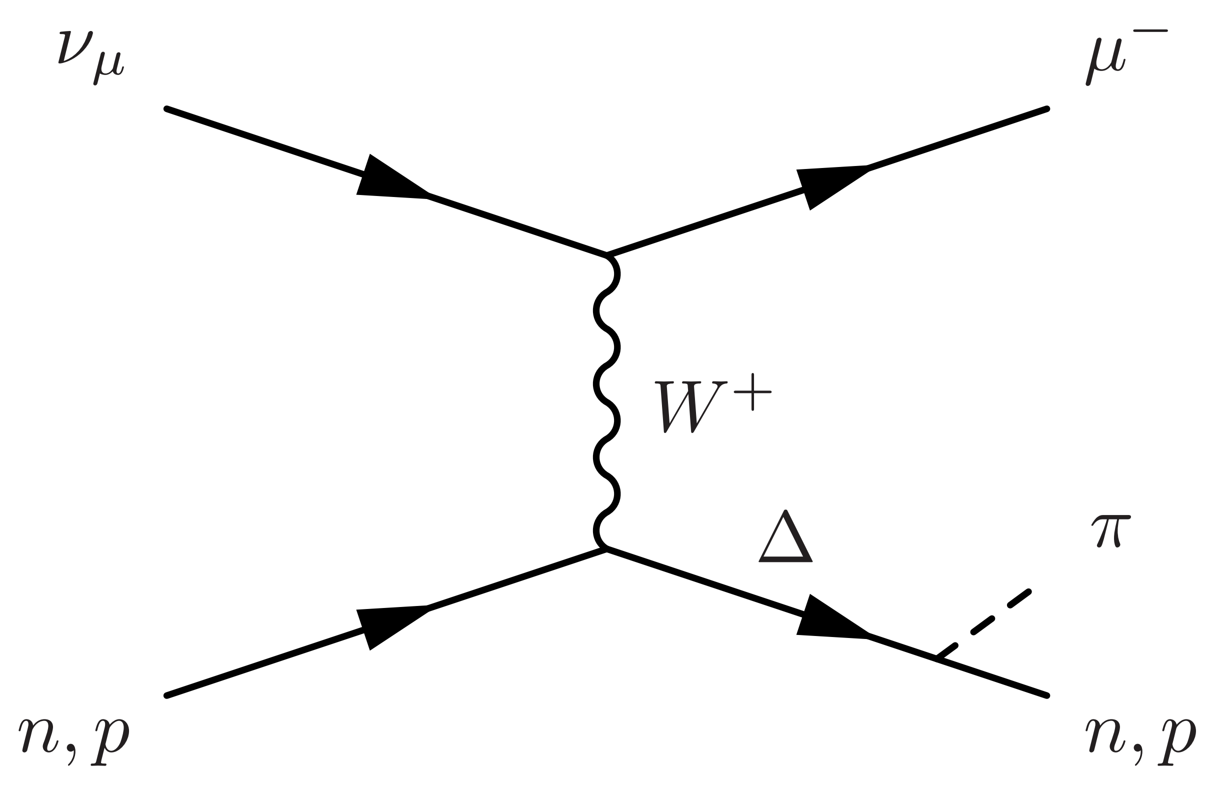

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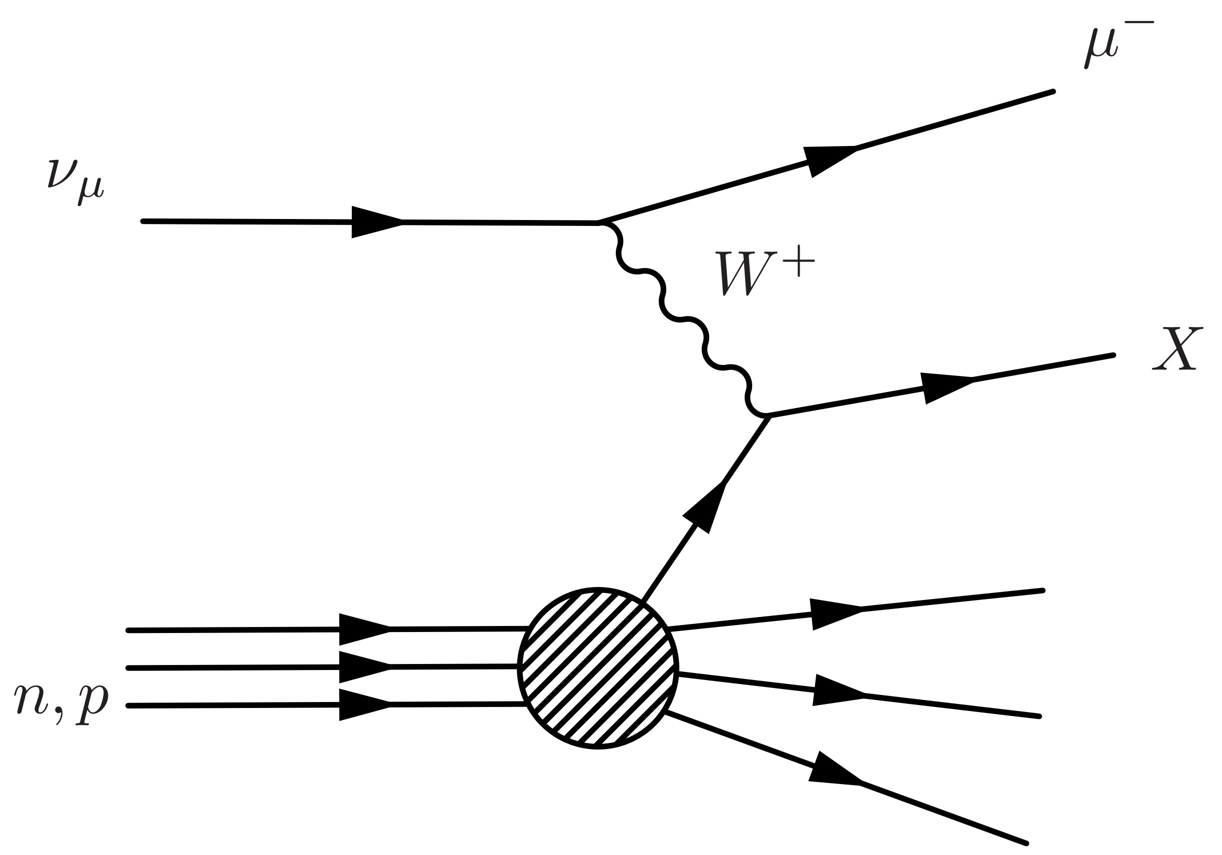

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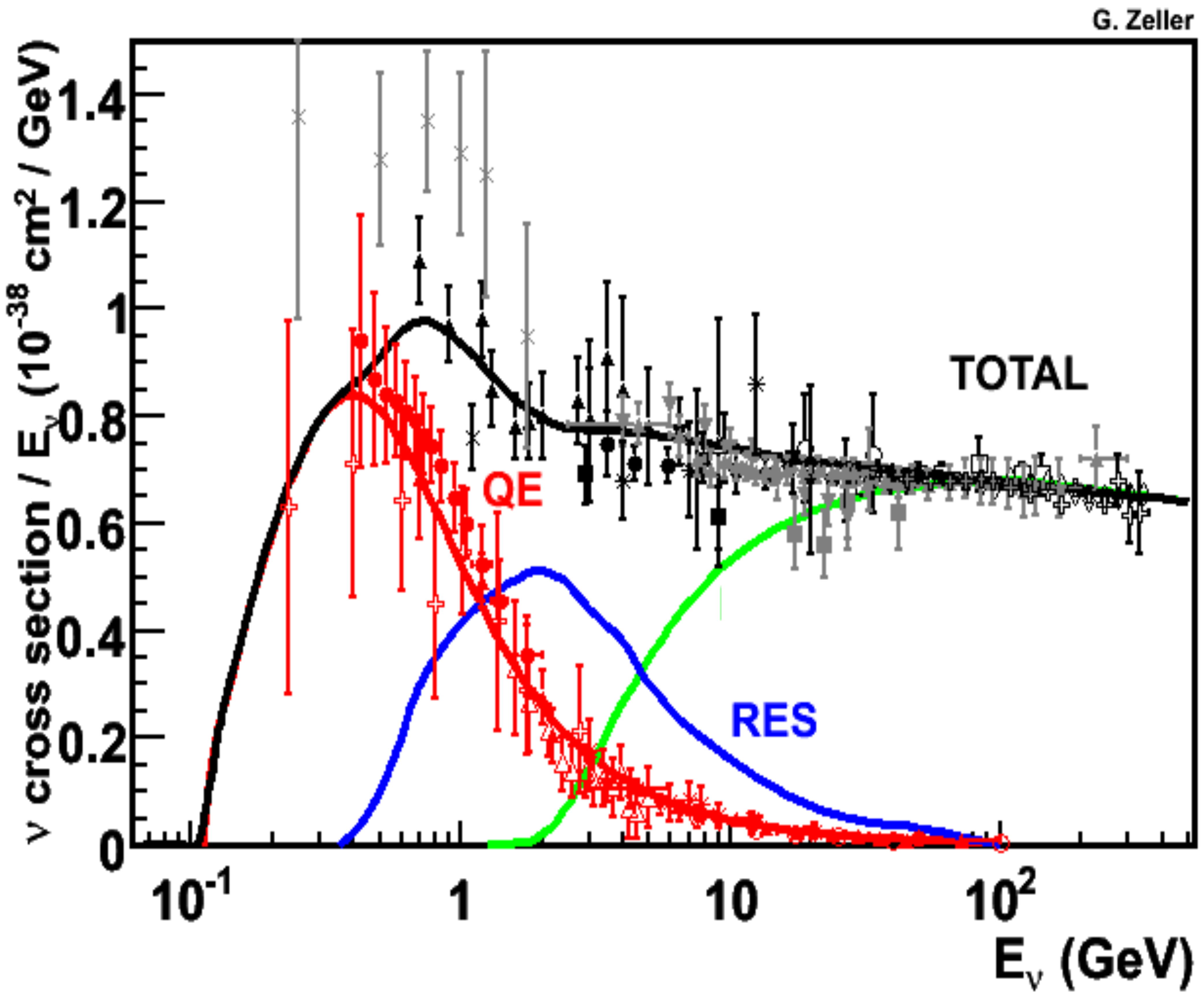

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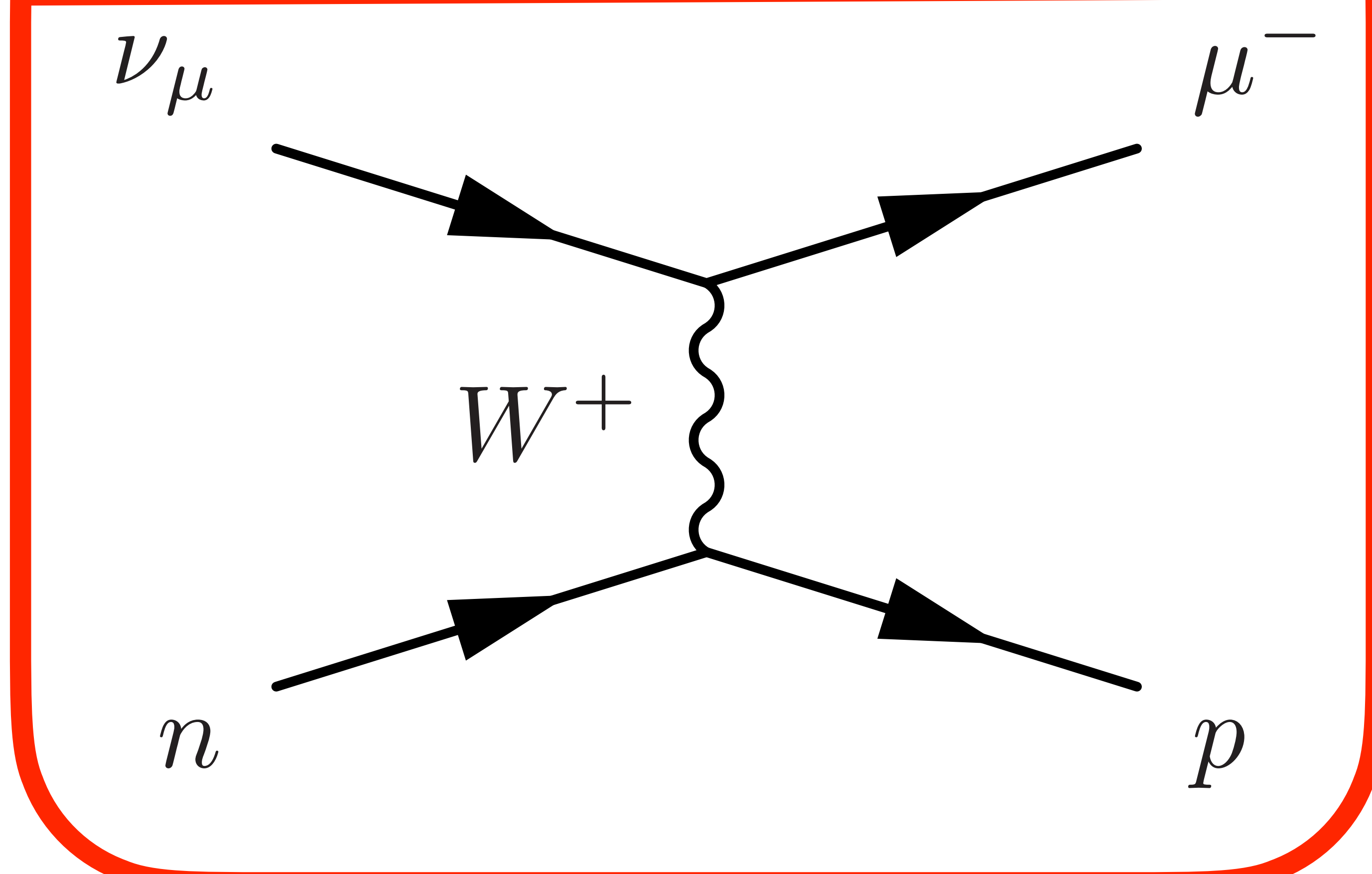
Quasi-elastic scattering



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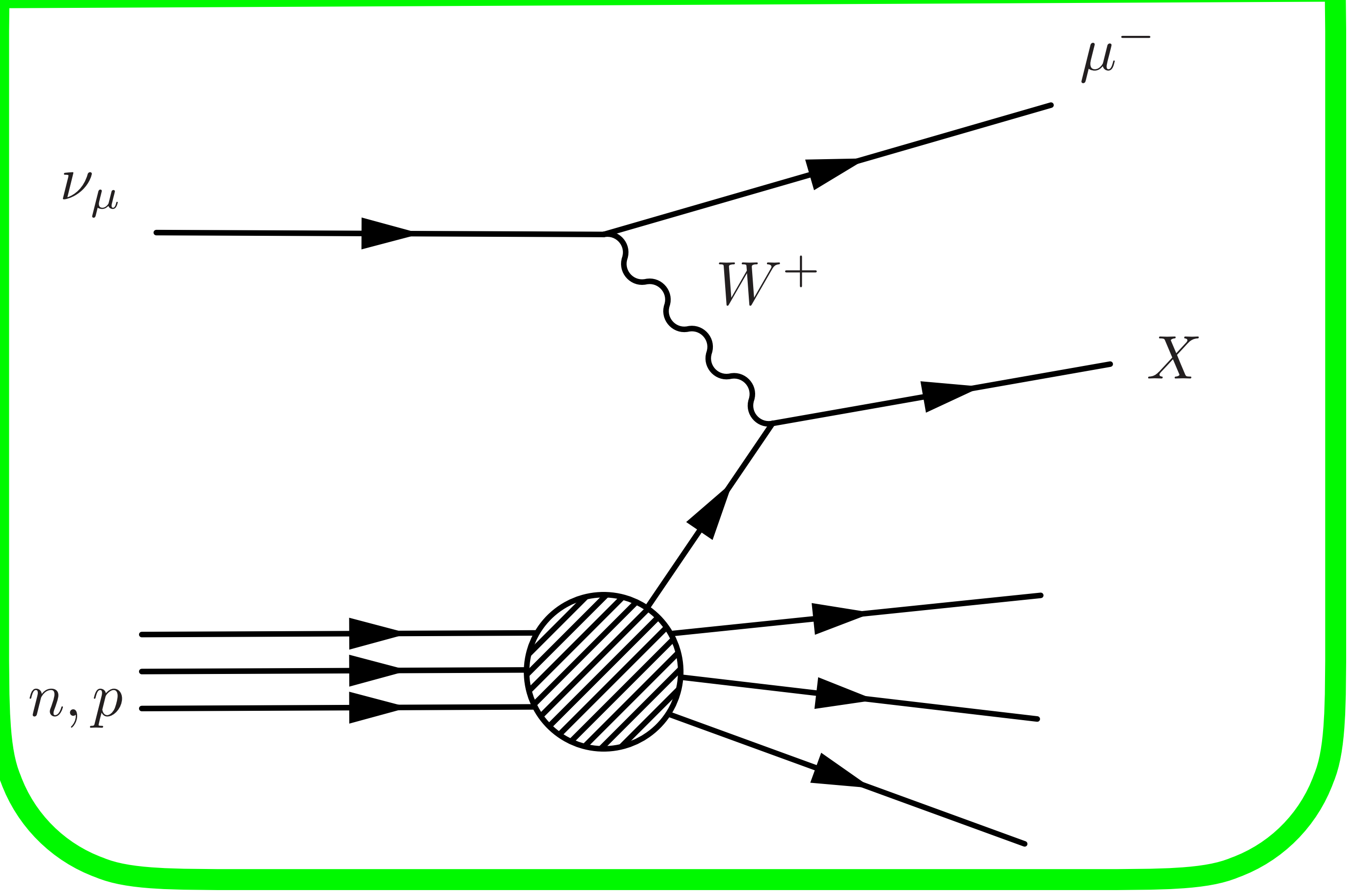

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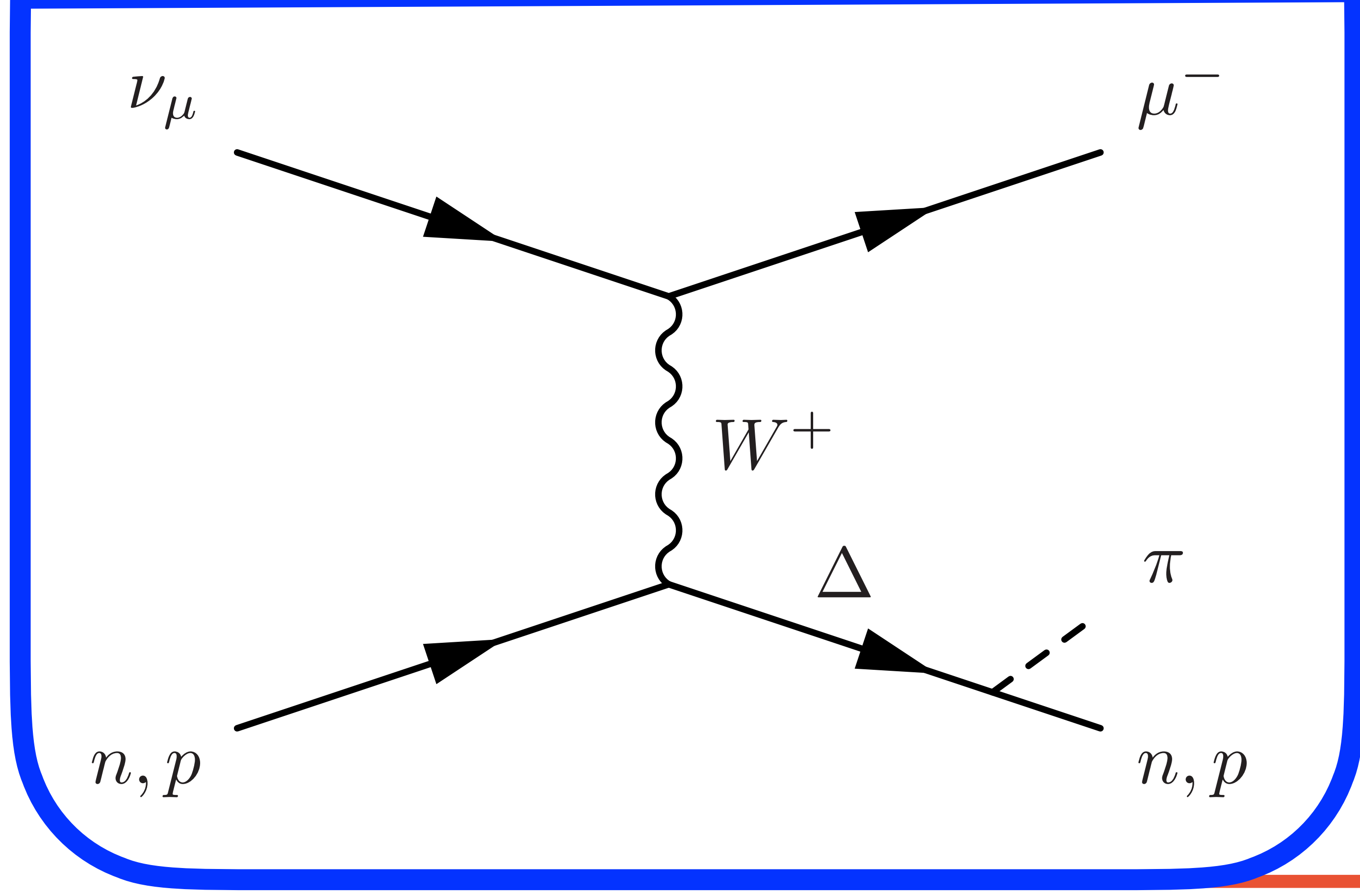

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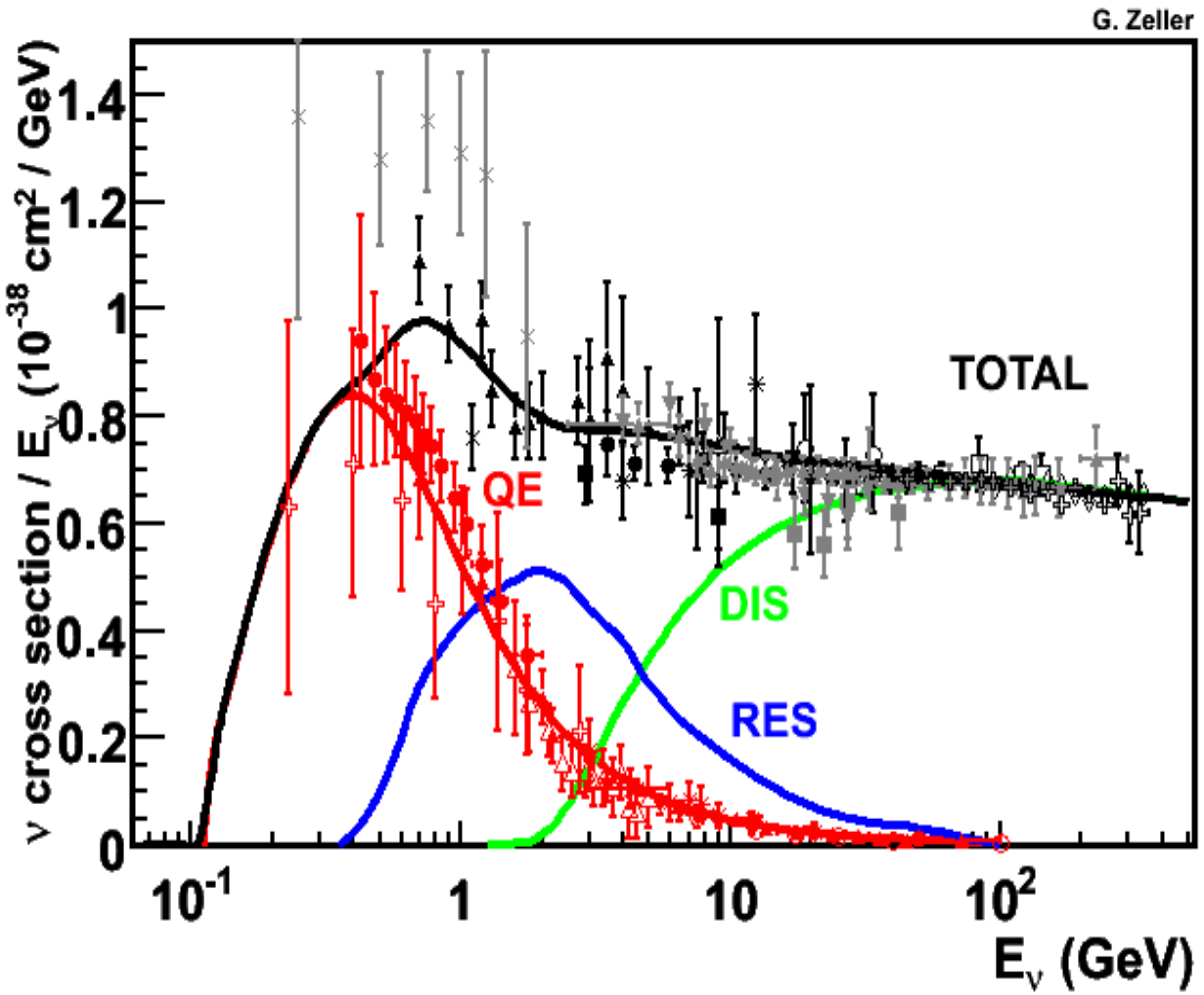

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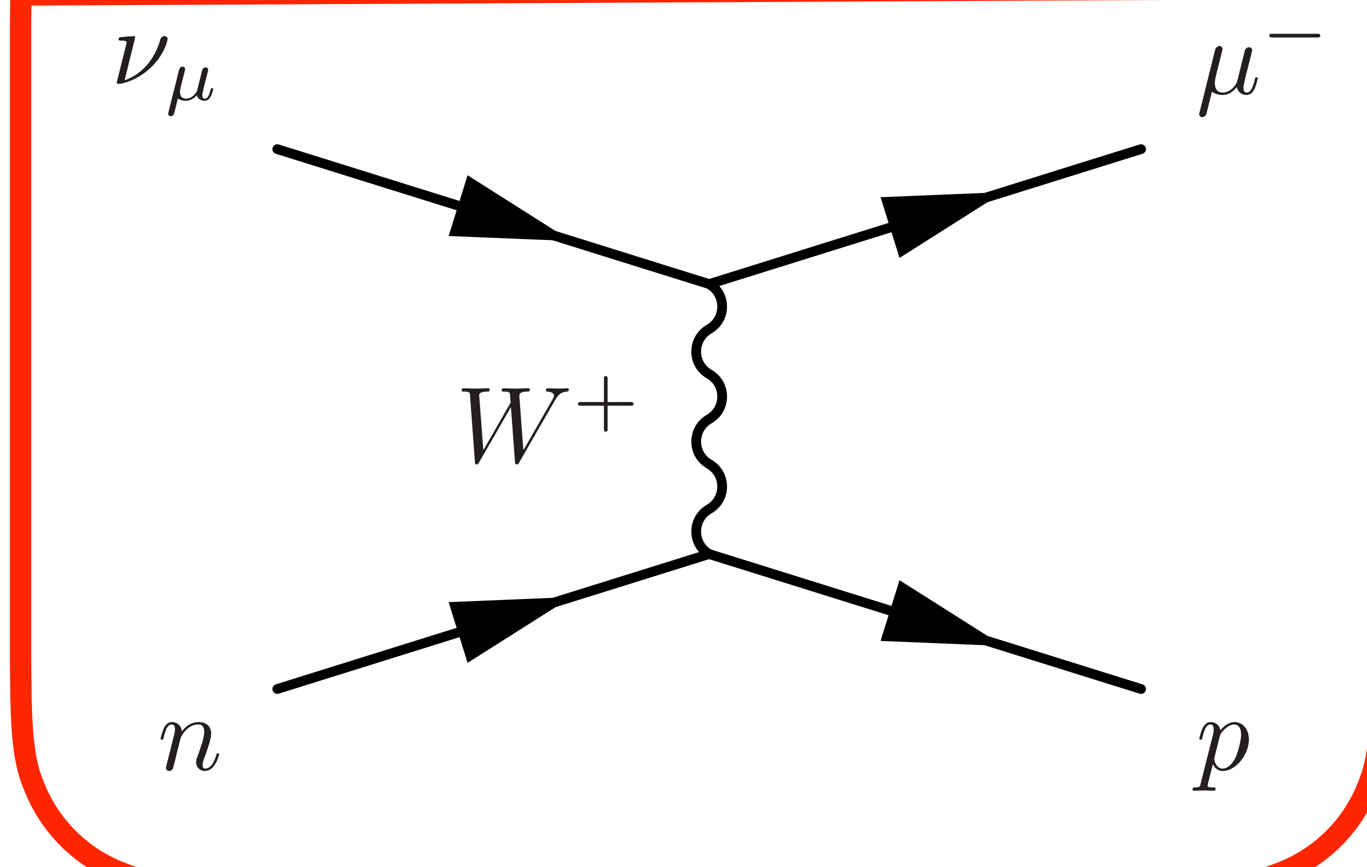

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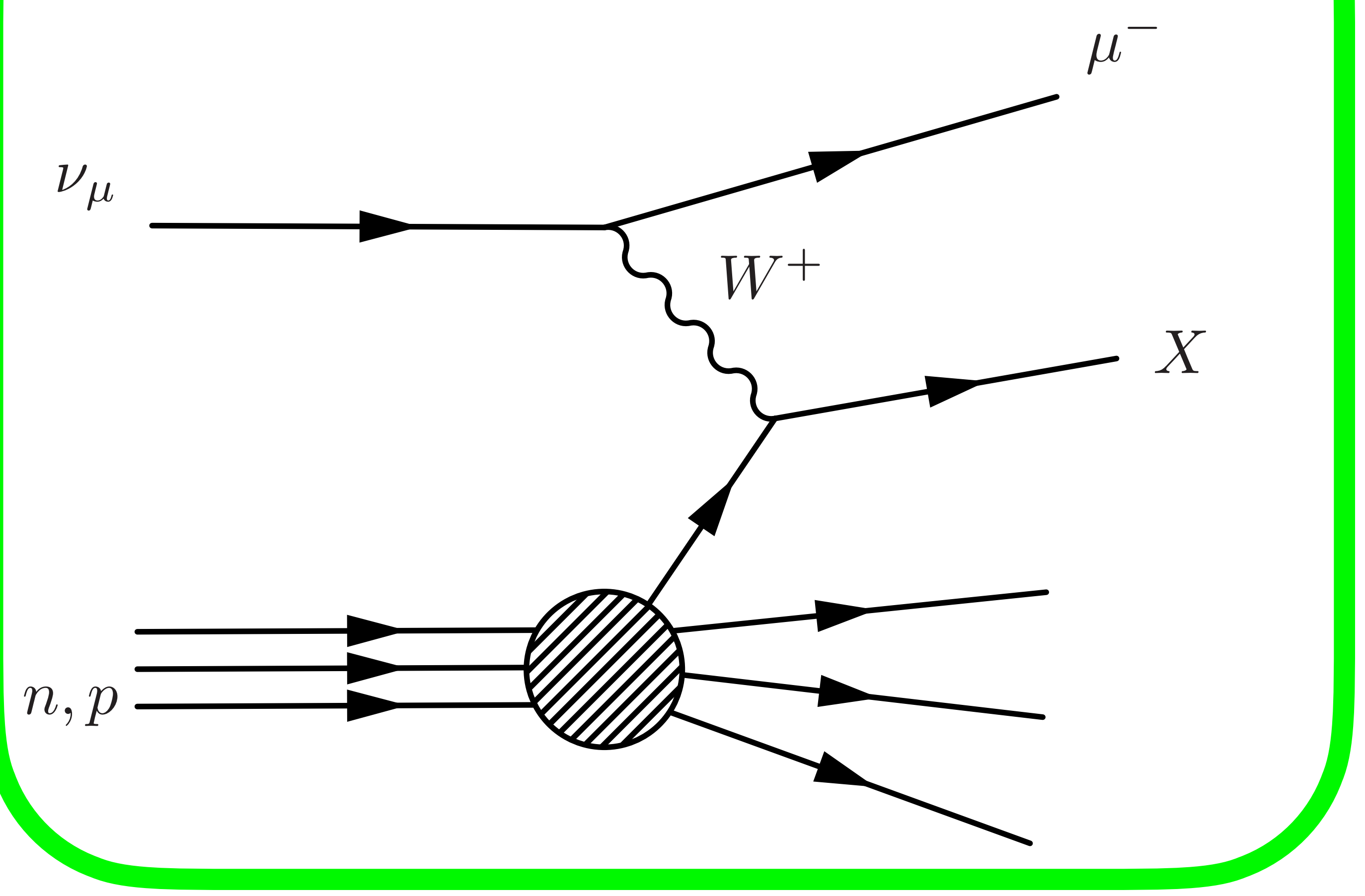

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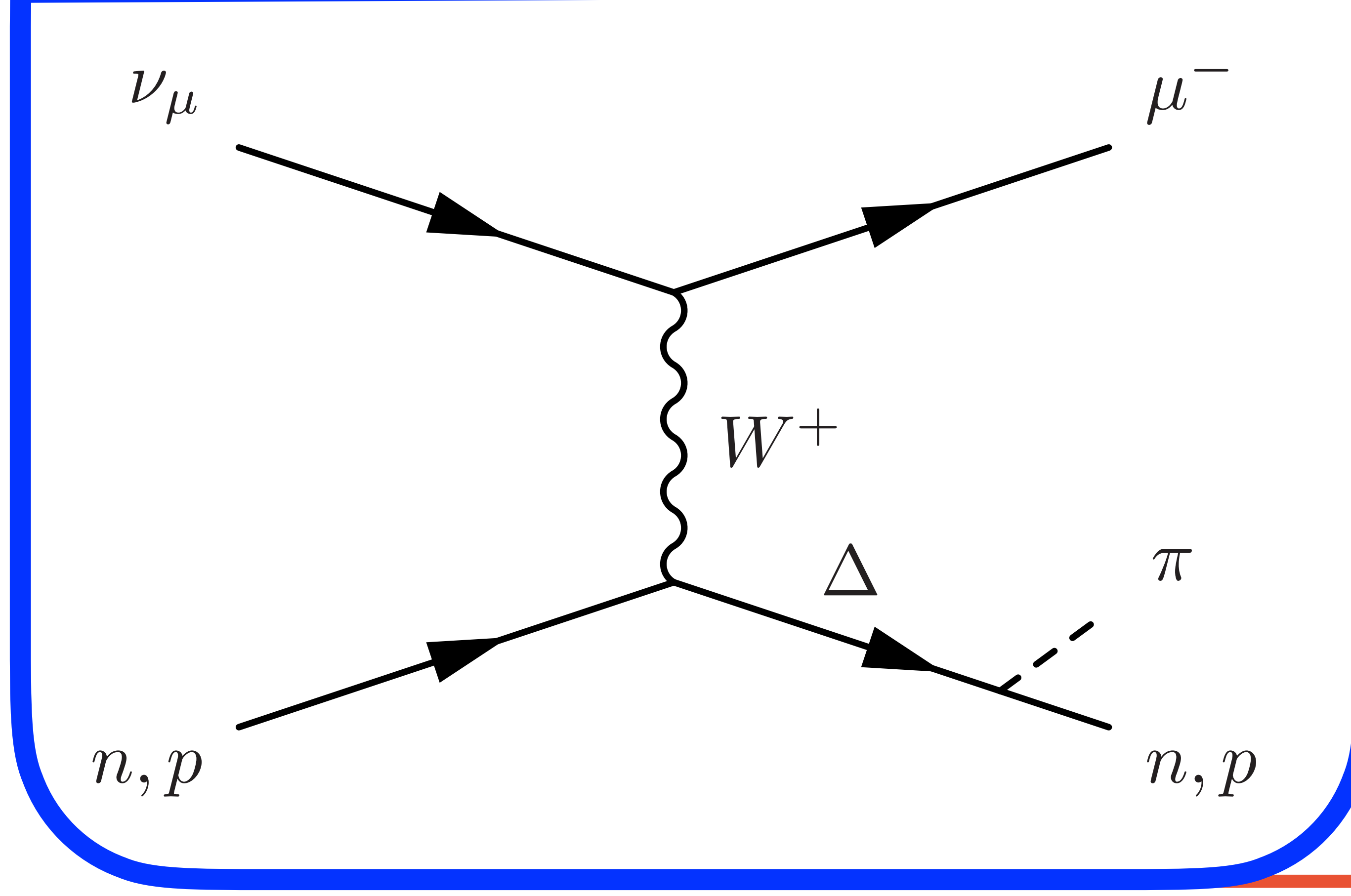

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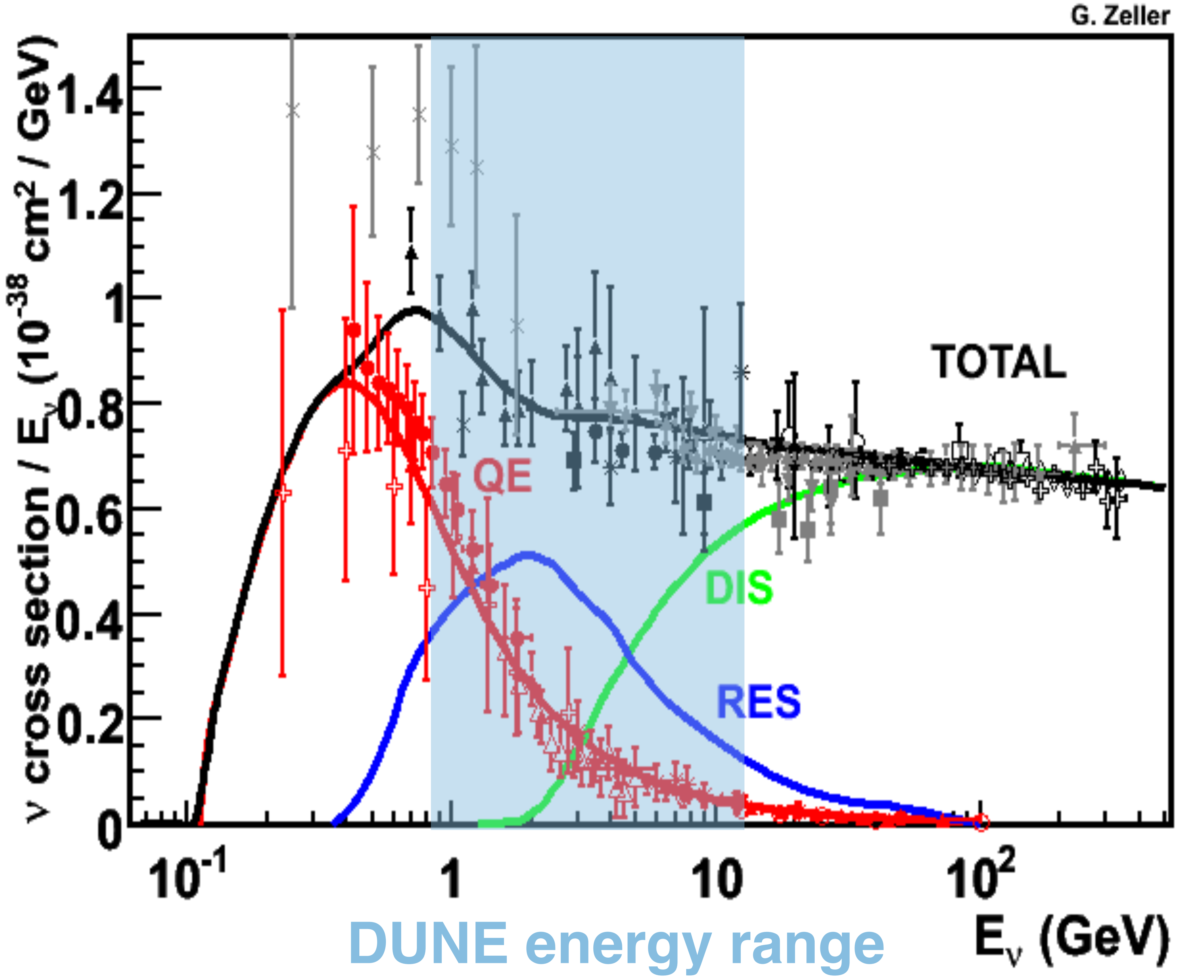
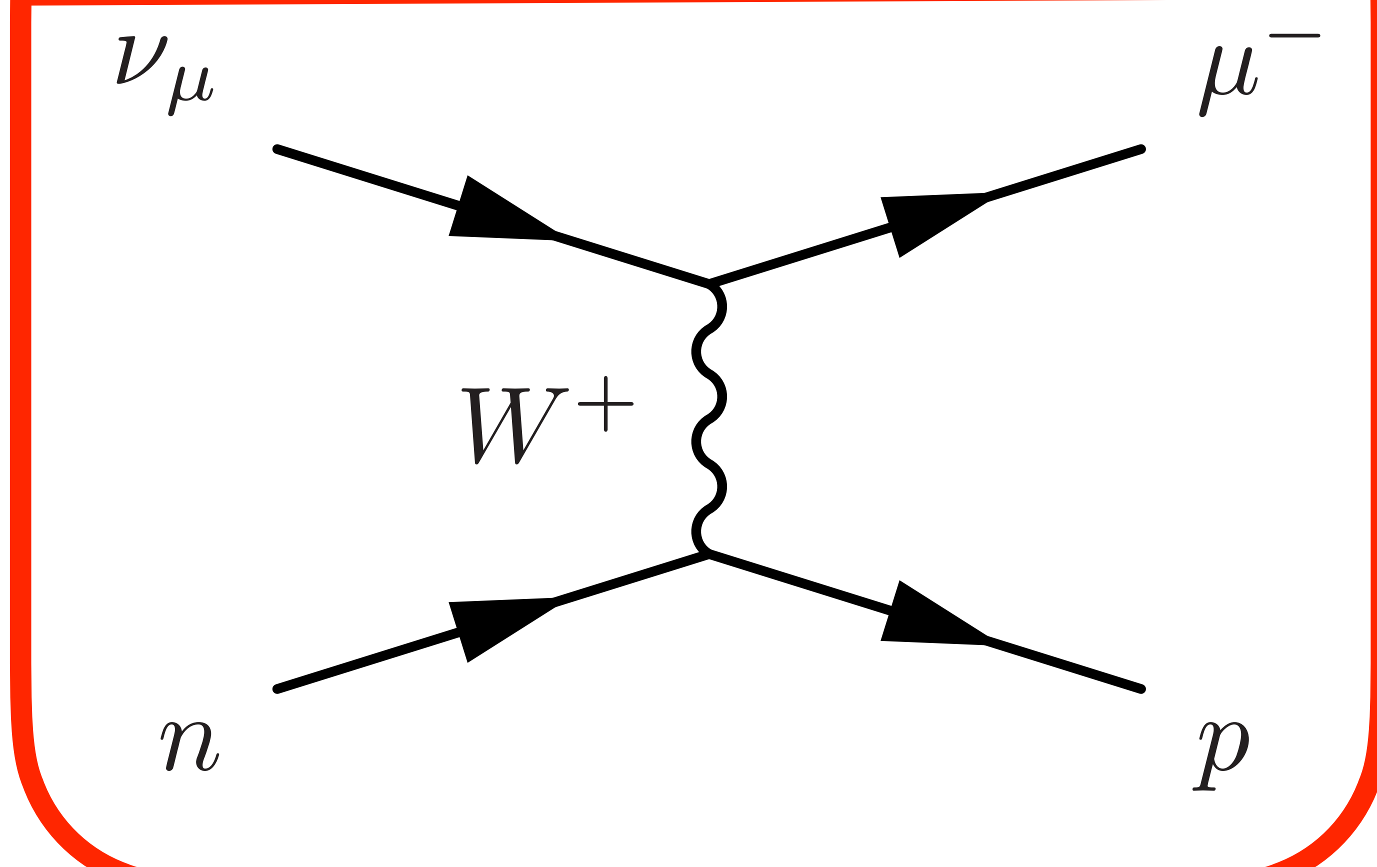


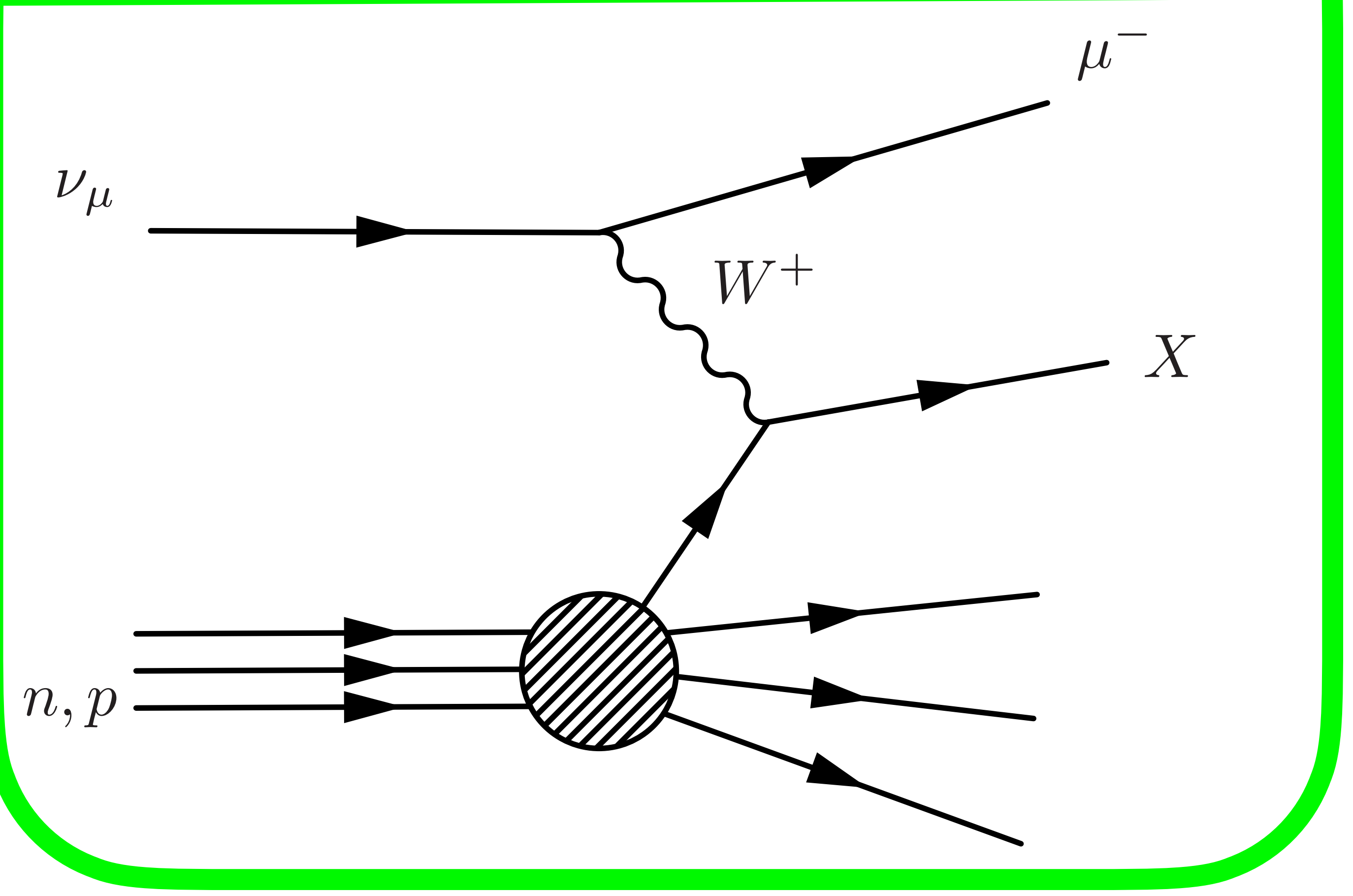
Remember… we don't know the neutrino energy

Three (charged-current) ways neutrinos interact with nucleons

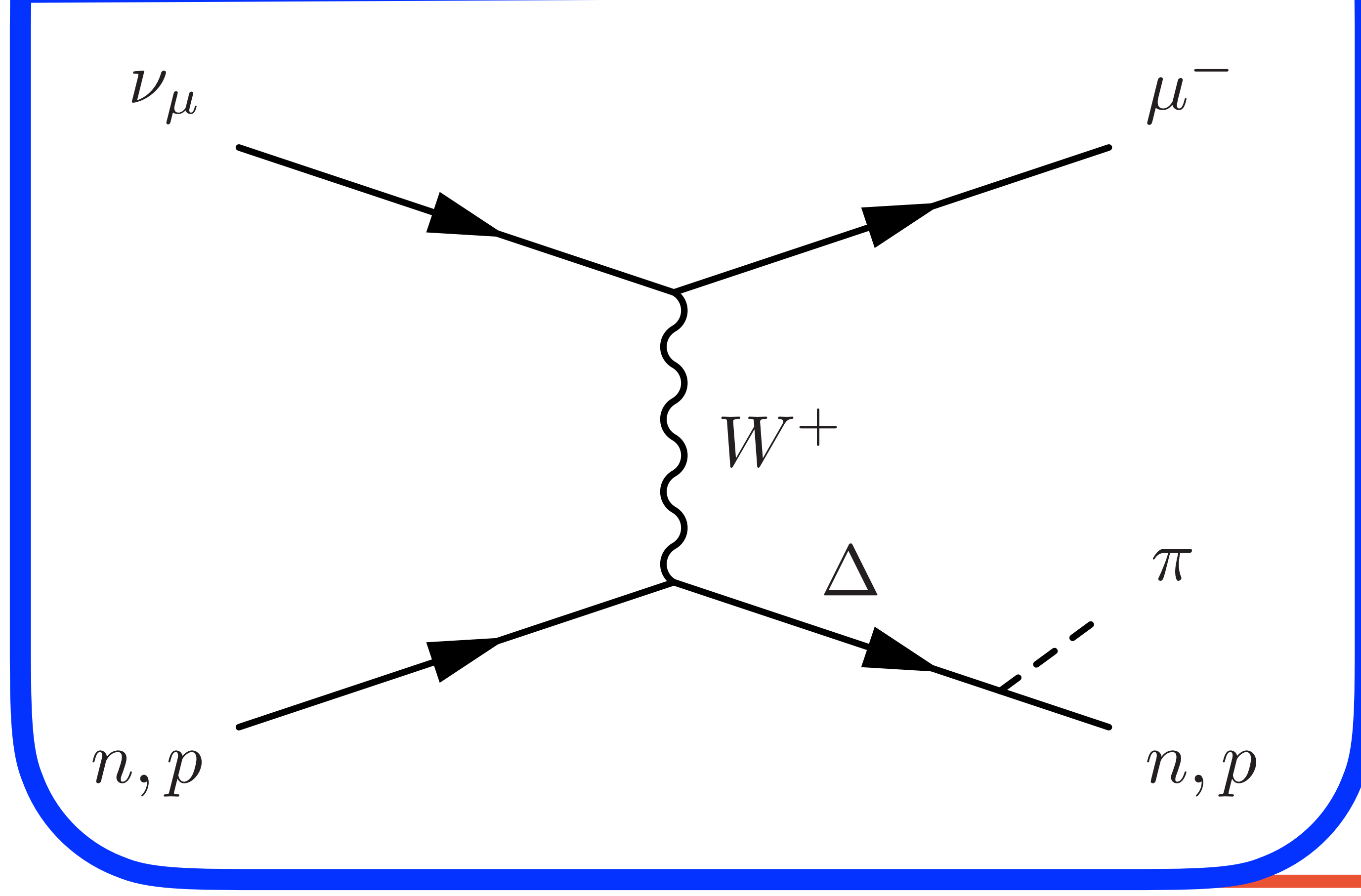
Quasi-elastic scattering



Deep inelastic scattering

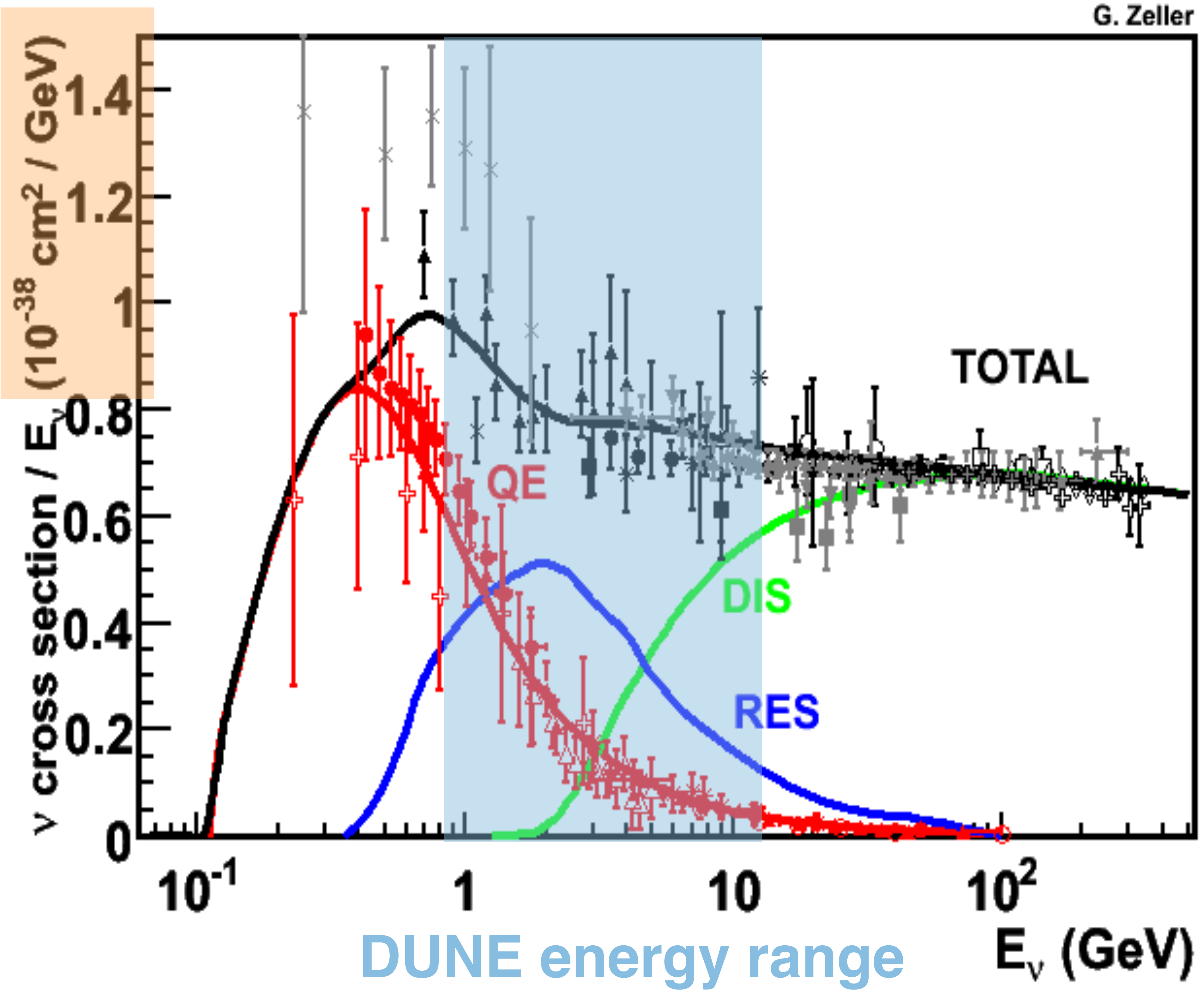


Resonant pion production



Different scattering modes happen at different energies. What do you think is happening in each of these?
Which do you think correspond to the red, blue, and green lines on the plot?
Hint - why does each curve have a low cut-off?

These cross-sections are very small!

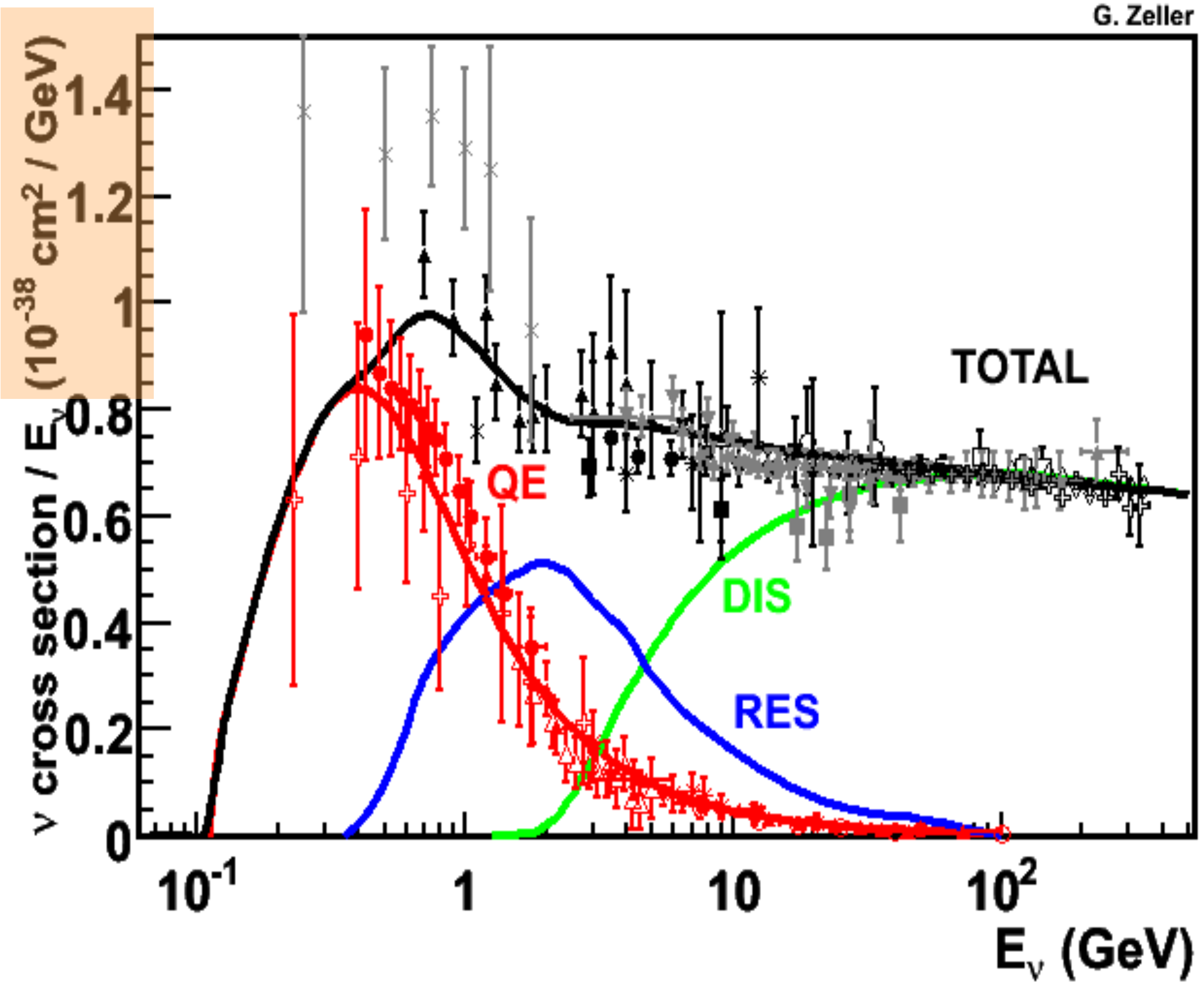


Remember… we don't know the neutrino energy

Interlude - cross sections

The **cross section** represents the probability that an interaction will occur…

…but it has units of **area** - why?



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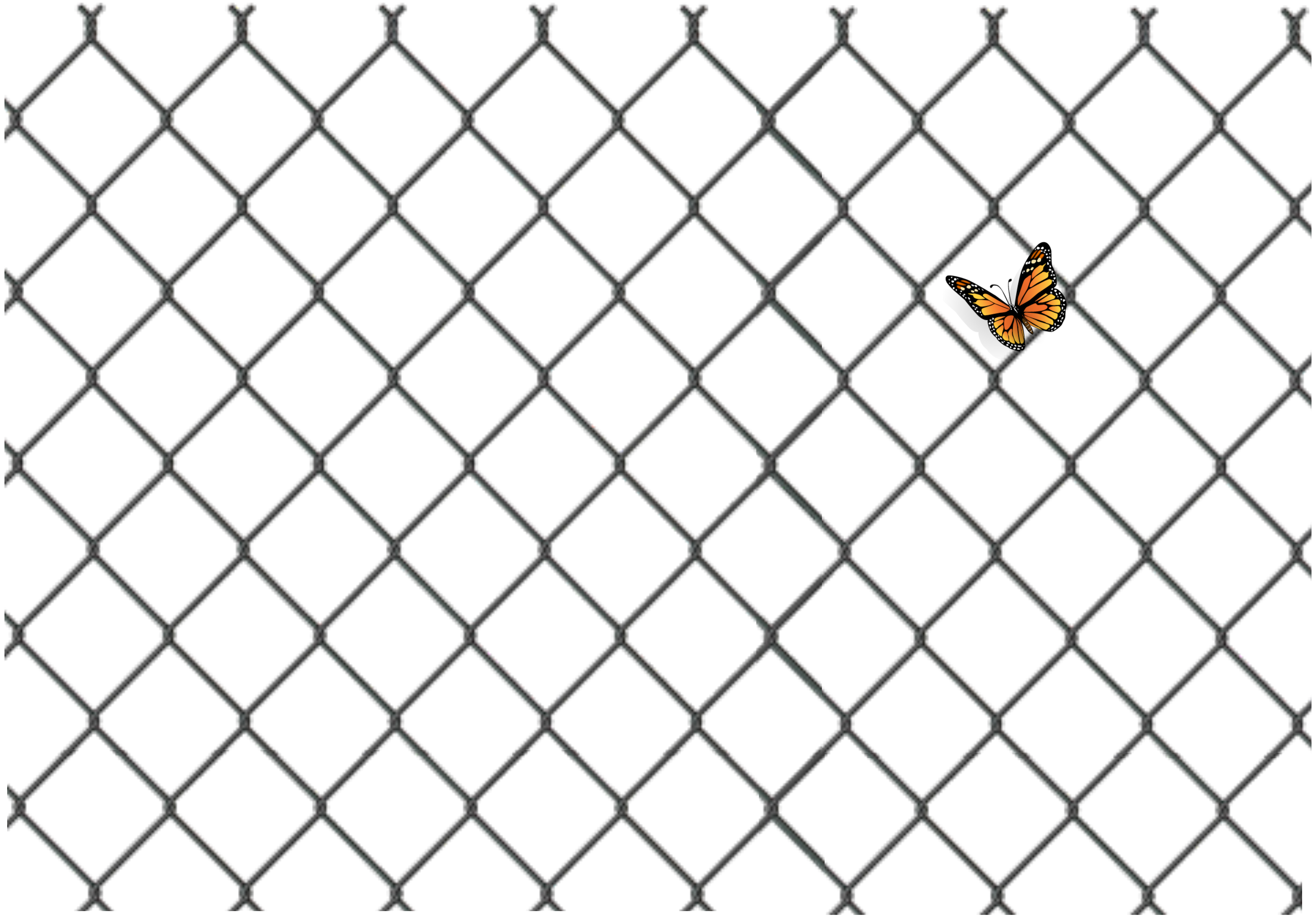

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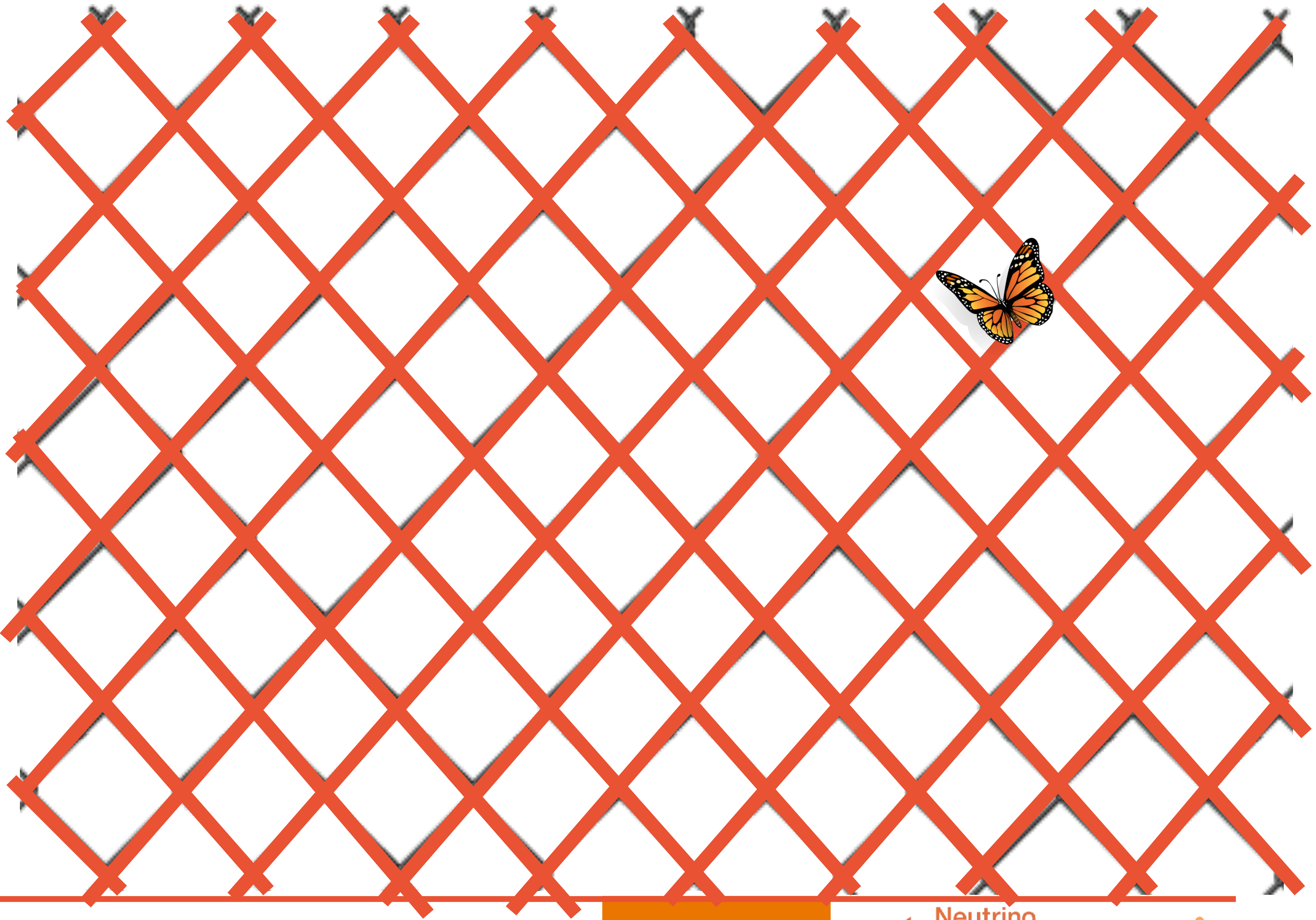


To the **dog**, this whole area is impassable

The **butterfly** is only stopped if it hits a wire

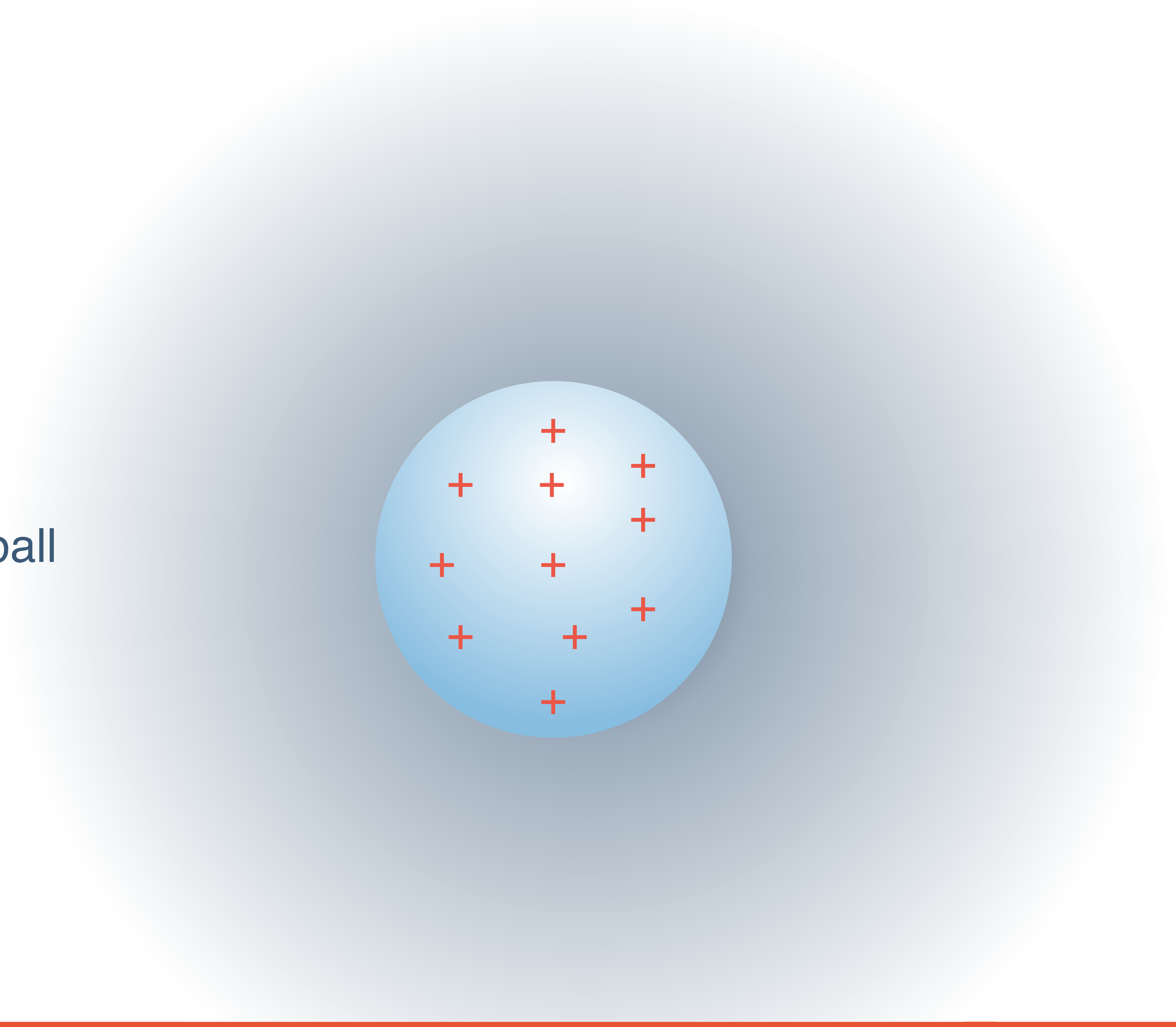
It's as if they see different areas

Interlude - cross sections

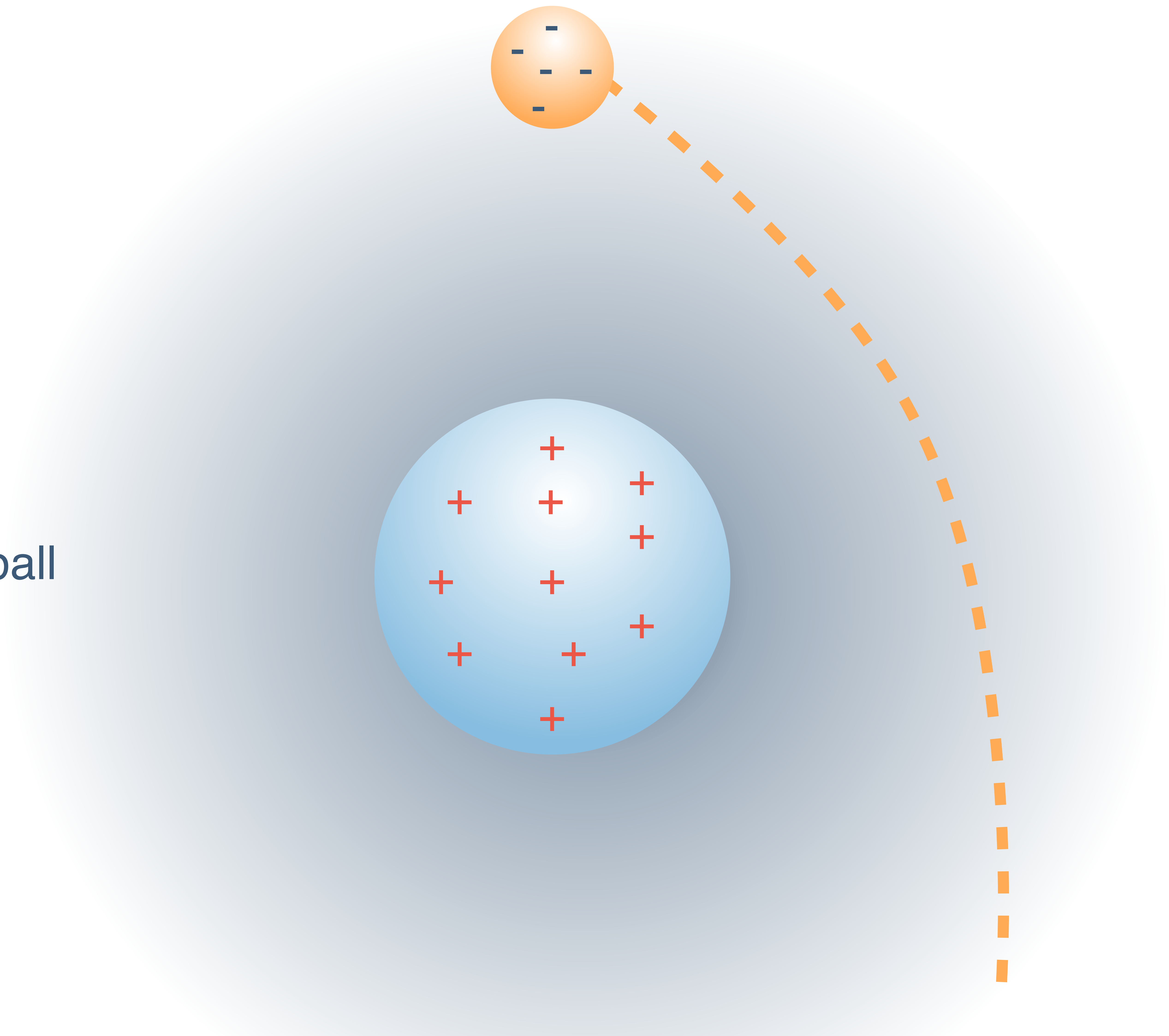
The **cross section** represents the probability that an interaction will occur…

…but it has units of **area** - why?

Now think of a positively-charged ball



Interlude - cross sections



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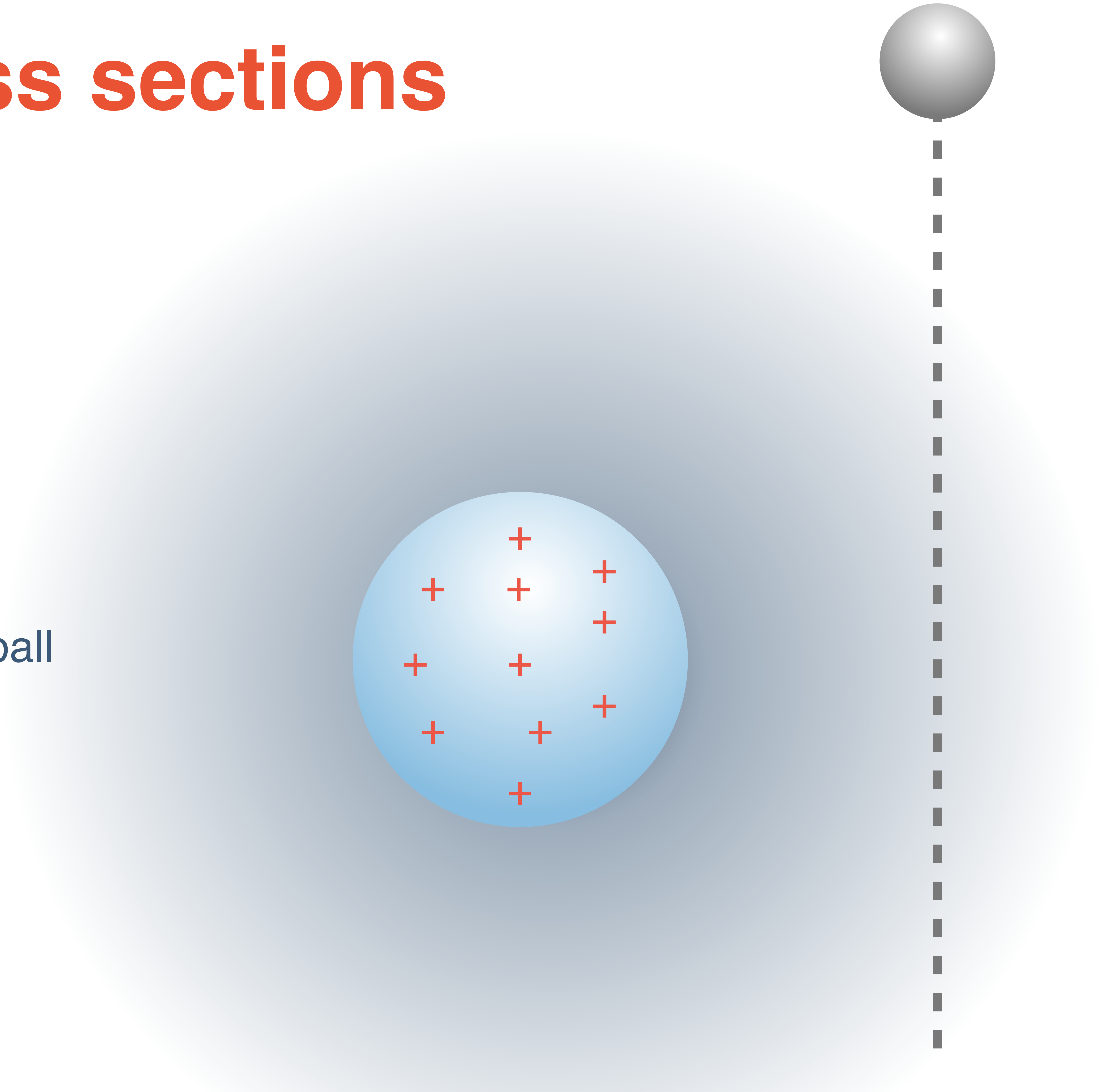
Now think of a positively-charged ball

A **negative ball** launched some way from it is deflected

Interlude - cross sections



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A **negative ball** launched some way from it is deflected

A **neutral ball** is unaffected…

Interlude - cross sections

The **cross section** represents the probability that an interaction will occur…

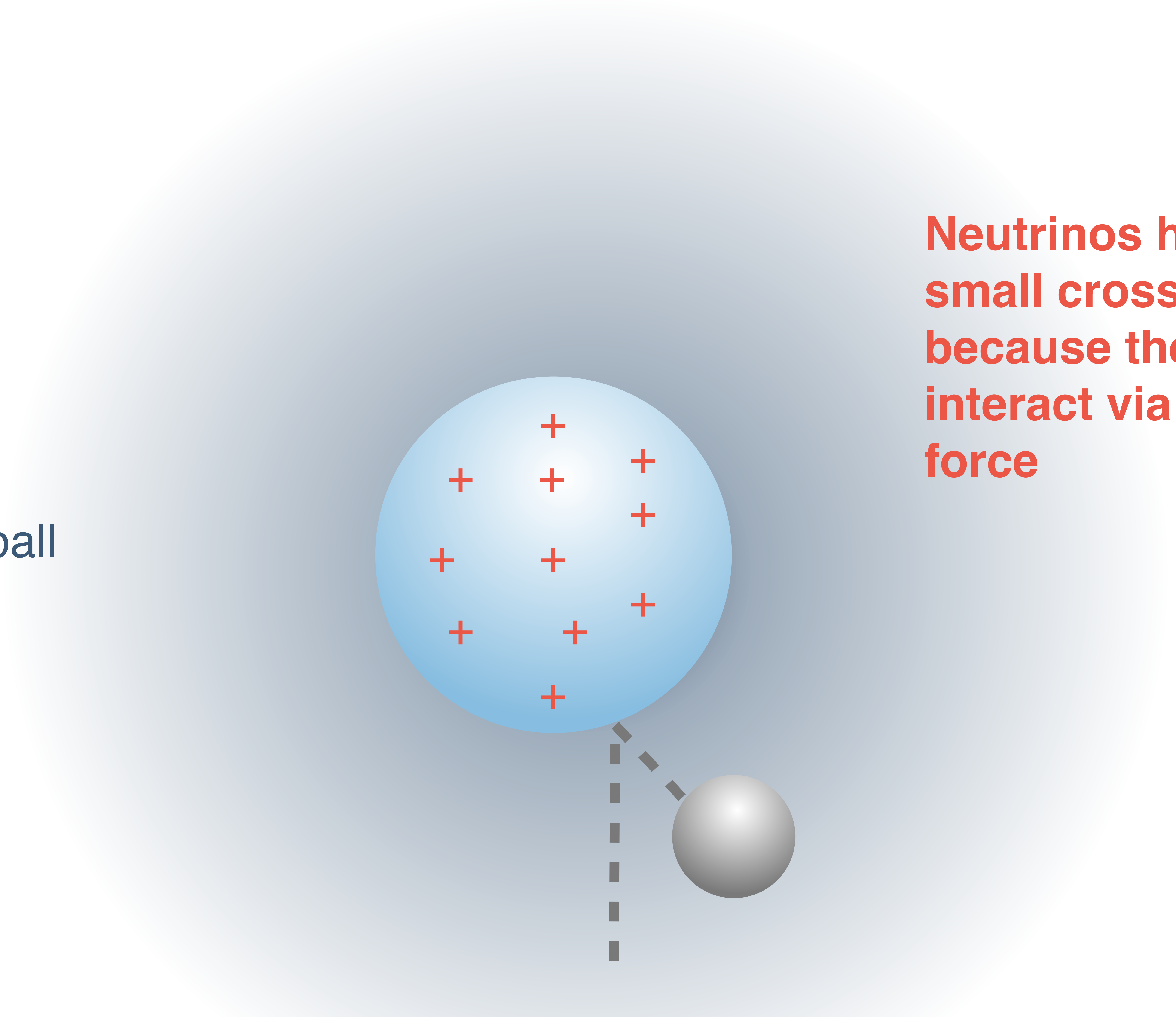
…but it has units of **area** - why?

Now think of a positively-charged ball

A **negative ball** launched some way from it is deflected

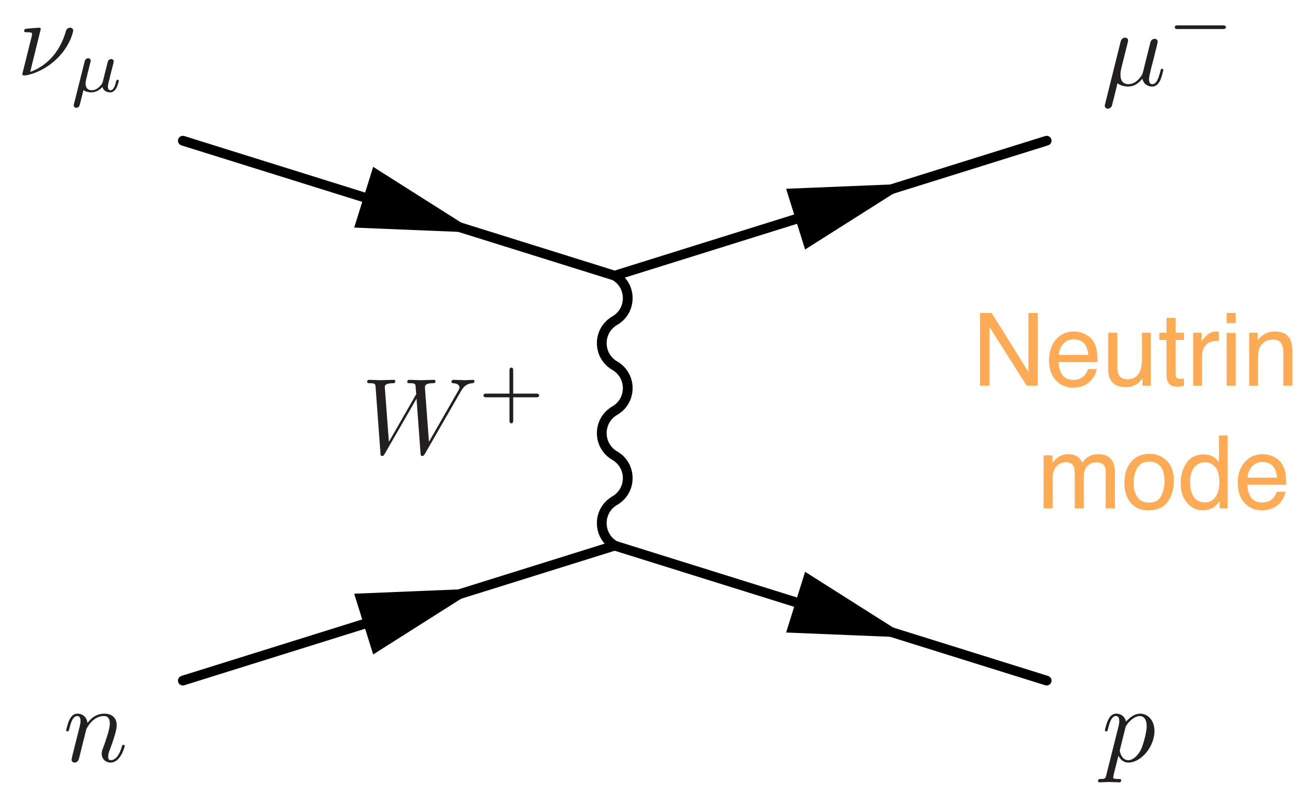
A **neutral ball** is unaffected…
… unless it scores a direct hit

It's as if they see different areas

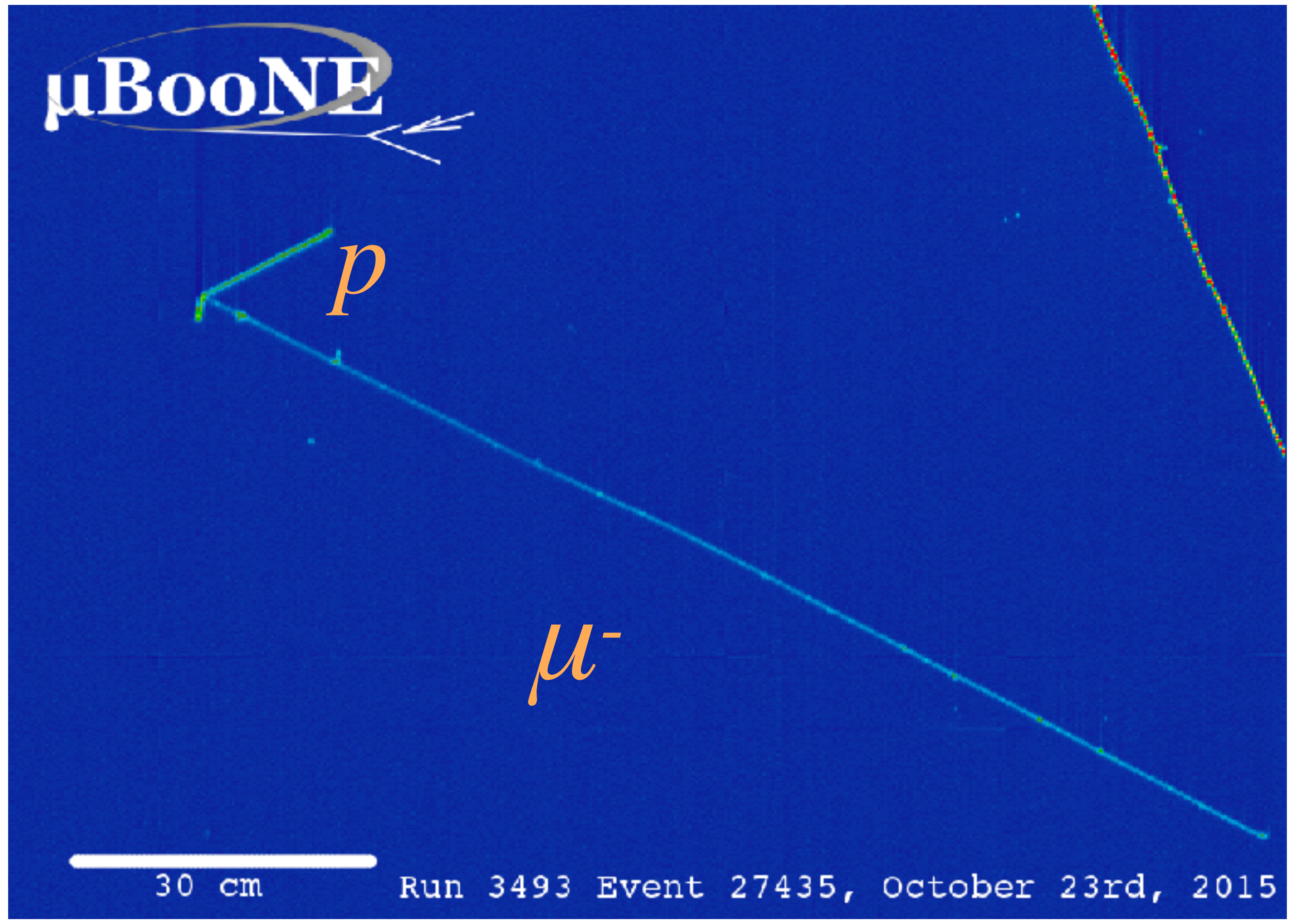


Neutrinos have very small cross sections because they only interact via the weak force

Charged-current quasi-elastic scattering - the “golden channel”



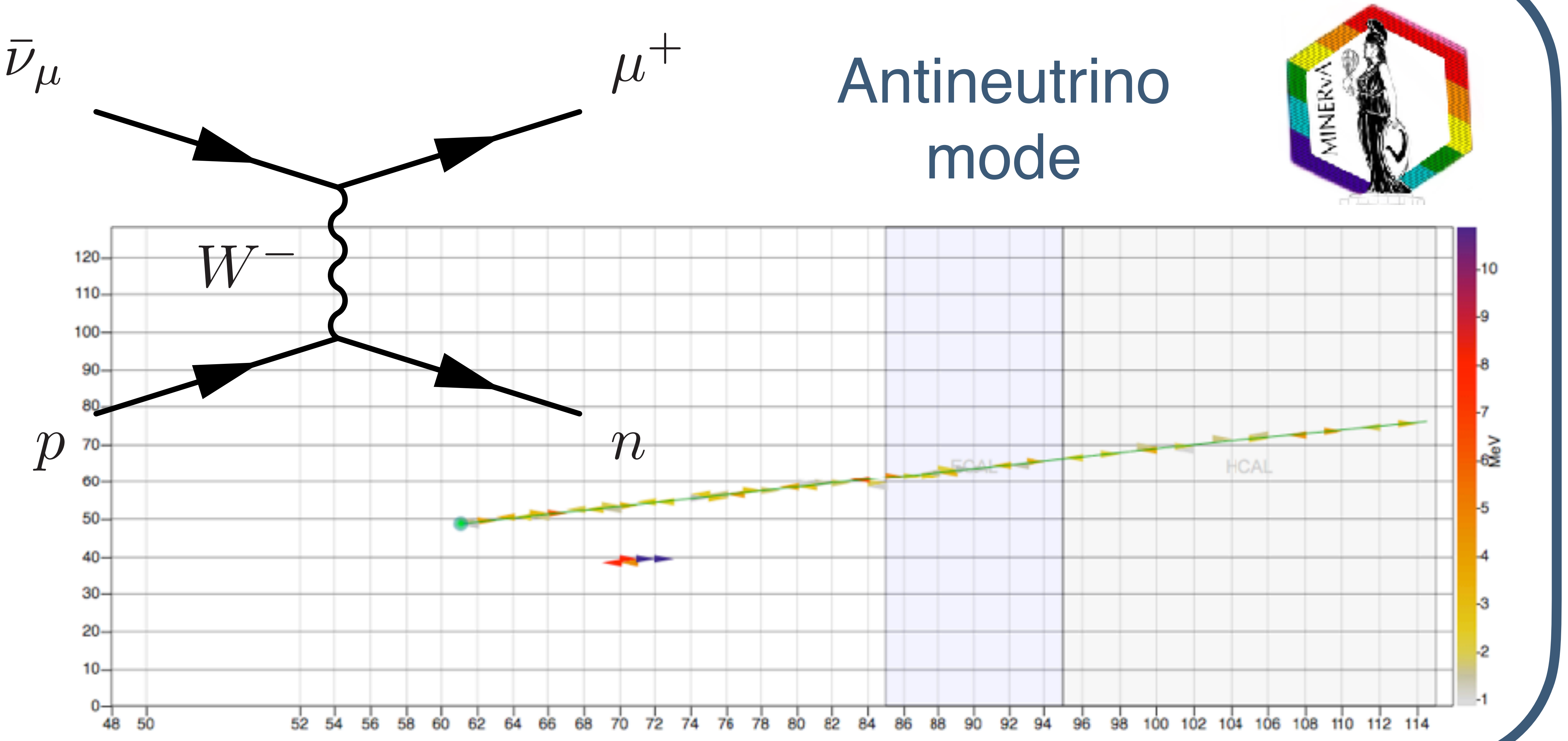
Neutrino mode



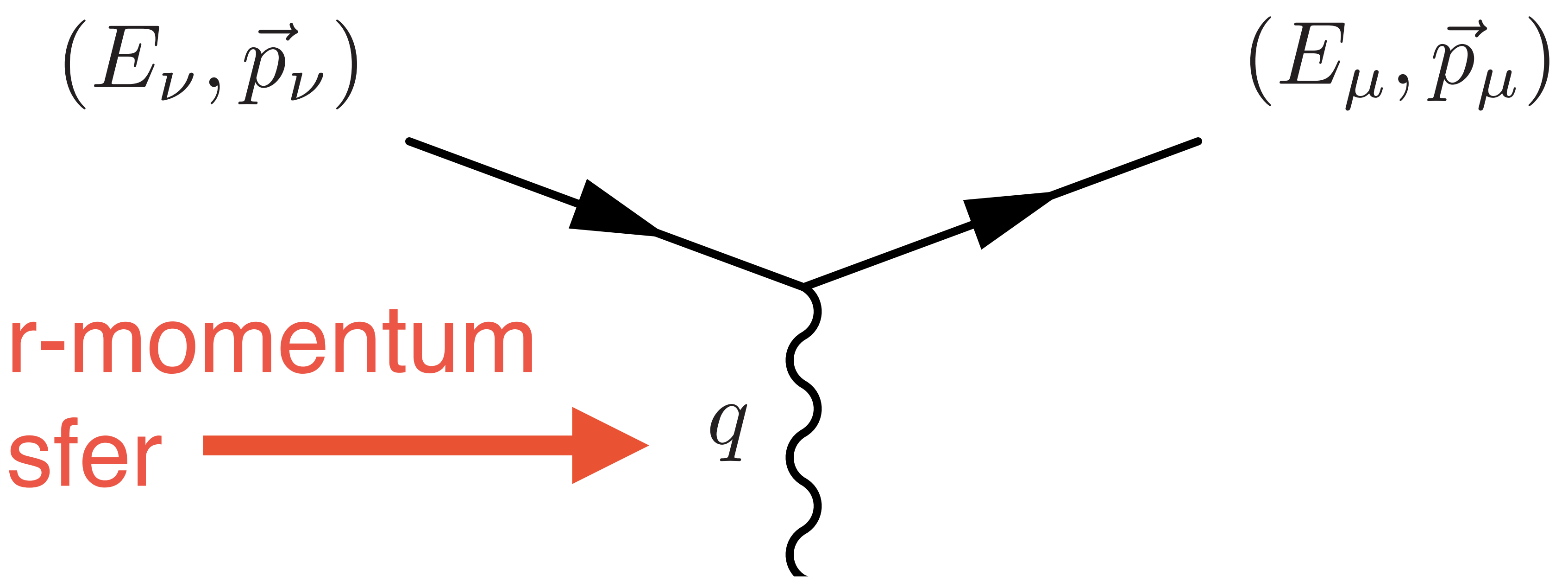
Simple final state - just a muon and a nucleon

Conserve energy and momentum:
calculate Q^2 and E_ν just from muon kinematics

Antineutrino mode

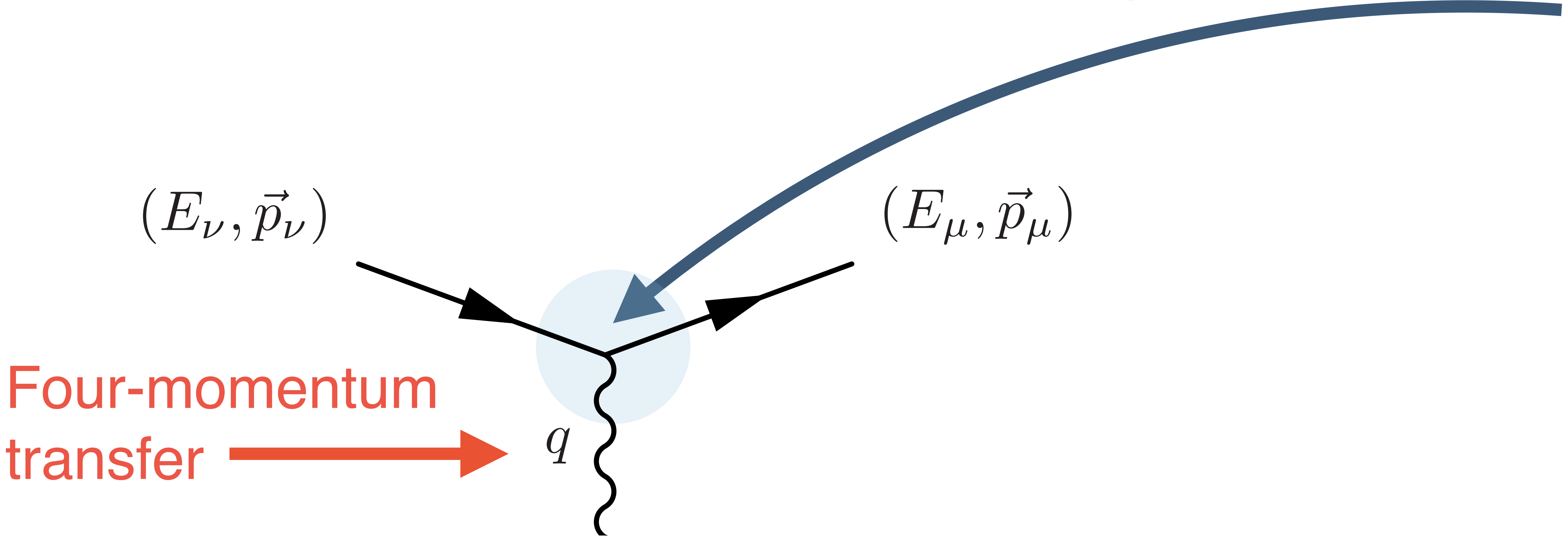


Interlude: introducing Q^2



Four-momentum transfer

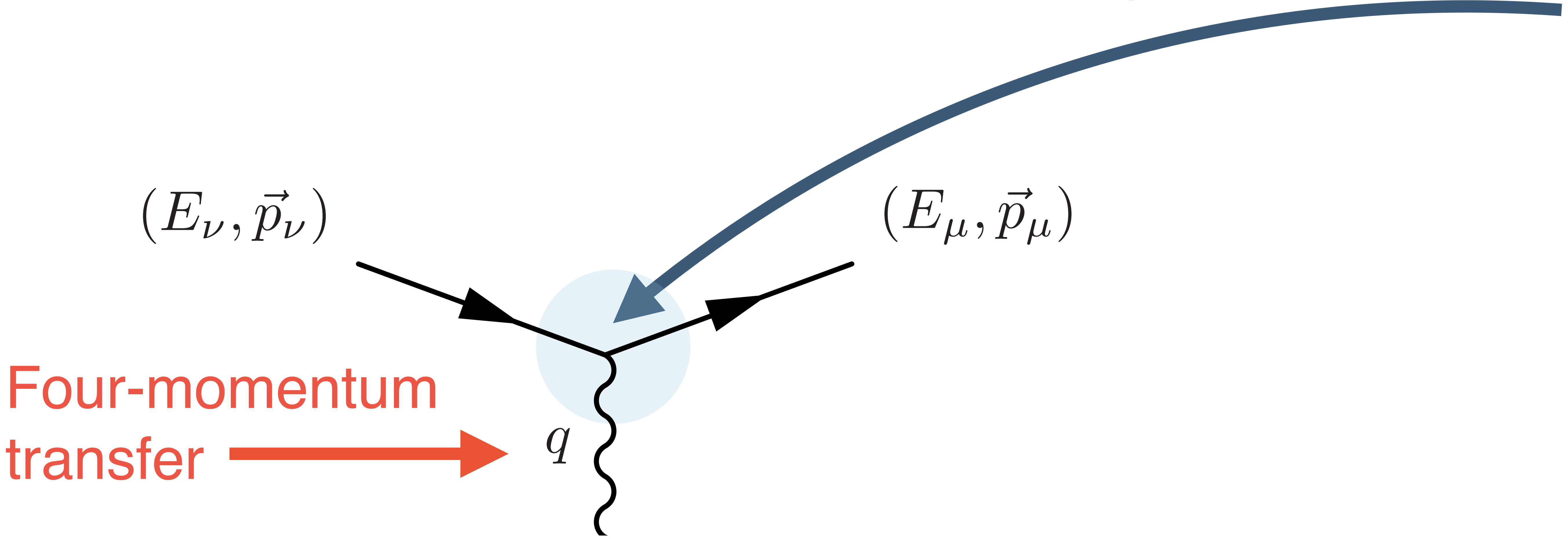
Interlude: introducing Q^2



Conserve four-momentum here:

$$q^2 = (p^\mu_\mu - p^\mu_\nu)^2$$
$$= (E_\mu - E_\nu)^2 - |\vec{p}_\mu - \vec{p}_\nu|^2$$

Interlude: introducing Q^2

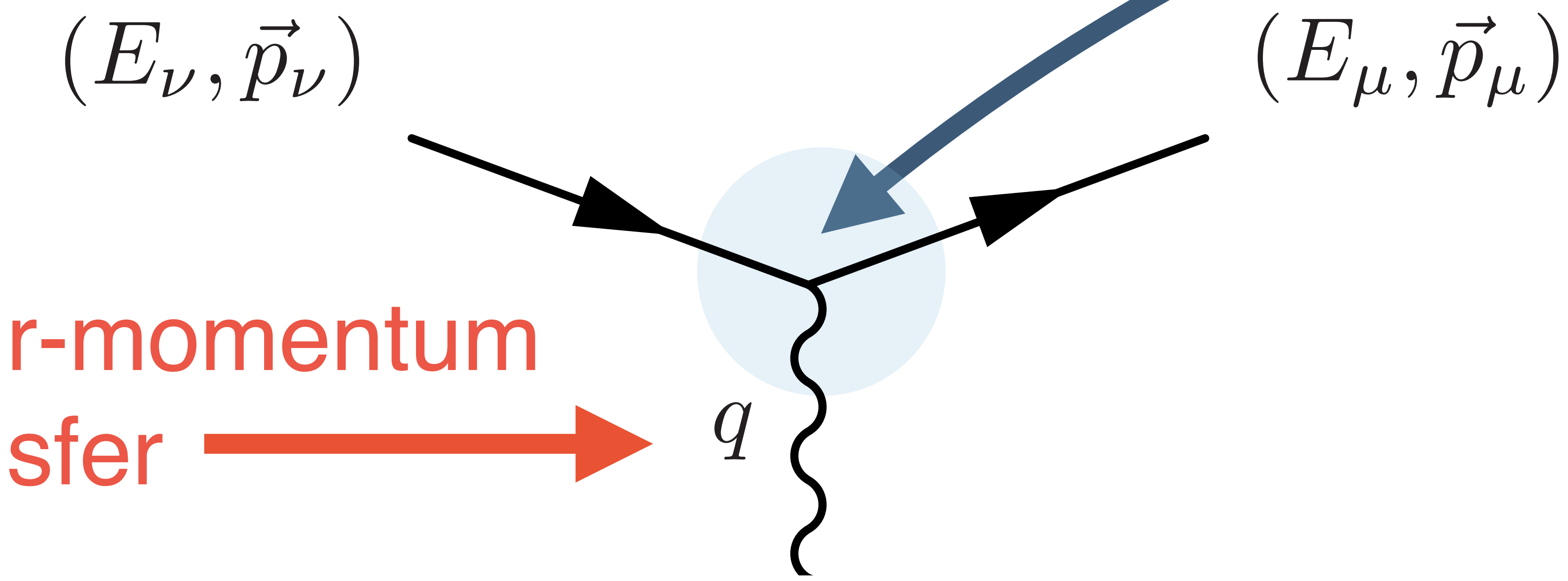


Conserve four-momentum here:

$$\boxed{q^2} = (p^\mu_\mu - p^\mu_\nu)^2$$
$$= \underbrace{\boxed{(E_\mu - E_\nu)^2}}_{\text{smaller}} - \underbrace{\boxed{|\vec{p}_\mu - \vec{p}_\nu|^2}}_{\text{bigger}}$$

negative quantity

Interlude: introducing Q^2



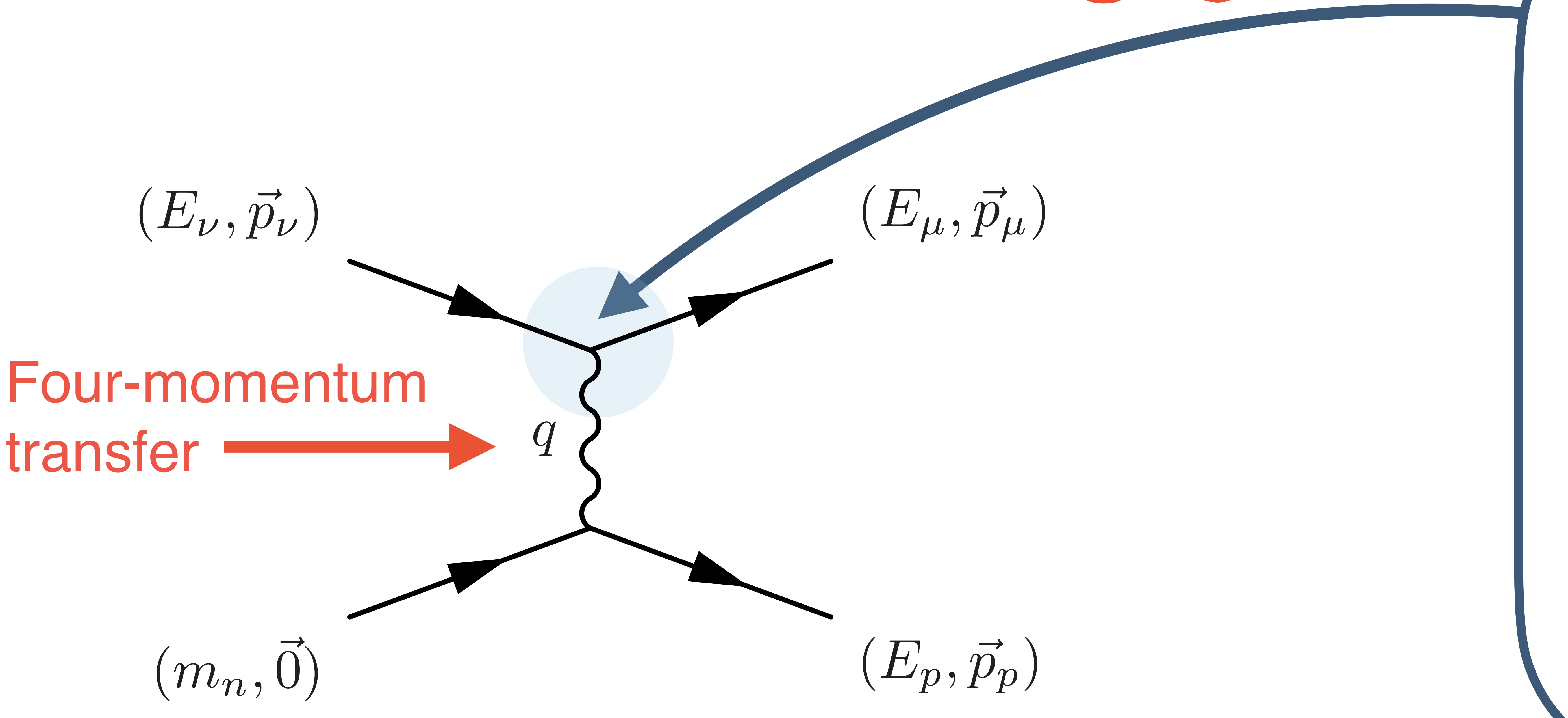
Four-momentum transfer

Conserve four-momentum here:

$$q^2 = (p^\mu_\mu - p^\mu_\nu)^2$$
$$= (E_\mu - E_\nu)^2 - |\vec{p}_\mu - \vec{p}_\nu|^2$$
$$Q^2 = -q^2$$
$$= |\vec{p}_\mu - \vec{p}_\nu|^2 - (E_\mu - E_\nu)^2$$
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Nucleon form factors depend on Q^2 (more on this later)

Interlude: introducing Q^2



Conserve four-momentum here:

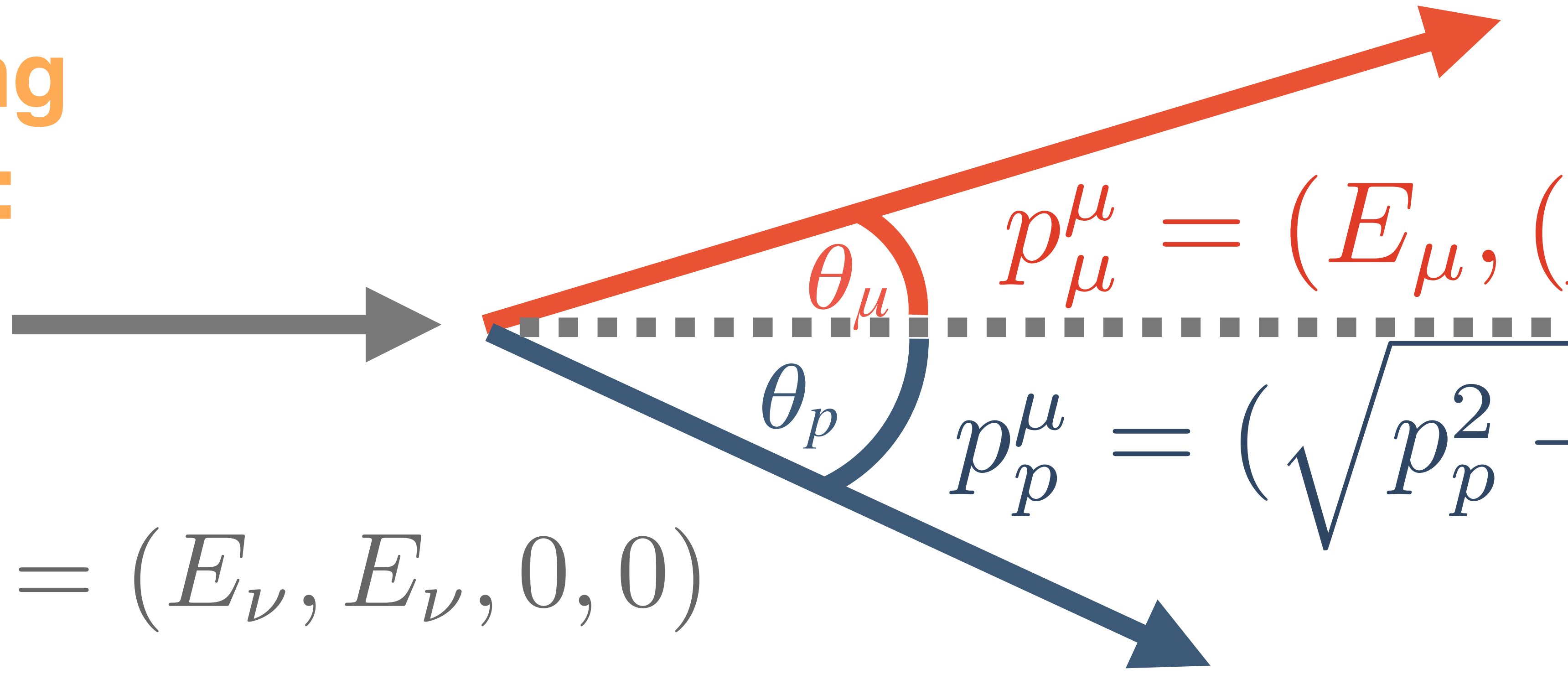
$$
\begin{aligned}
q^2 &= (p^\mu_\mu - p^\mu_\nu)^2 \\
&= (E_\mu - E_\nu)^2 - |\vec{p}_\mu - \vec{p}_\nu|^2 \\
Q^2 &= -q^2 \\
&= |\vec{p}_\mu - \vec{p}_\nu|^2 - (E_\mu - E_\nu)^2
\end{aligned}
$$

$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Nucleon form factors depend on Q^2 (more on this later)

For quasi-elastic scattering from a stationary neutron:

Conserve energy and momentum to calculate $E_\nu\ (E_\mu, \theta_\mu)$

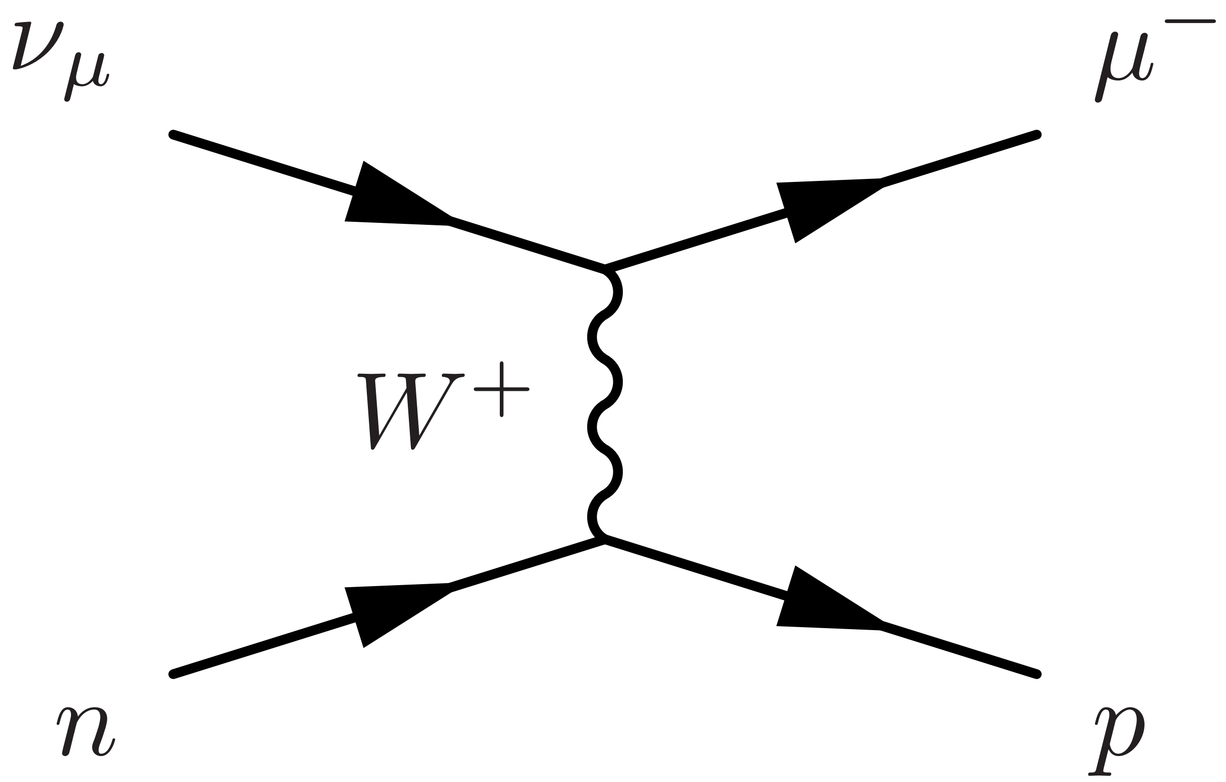


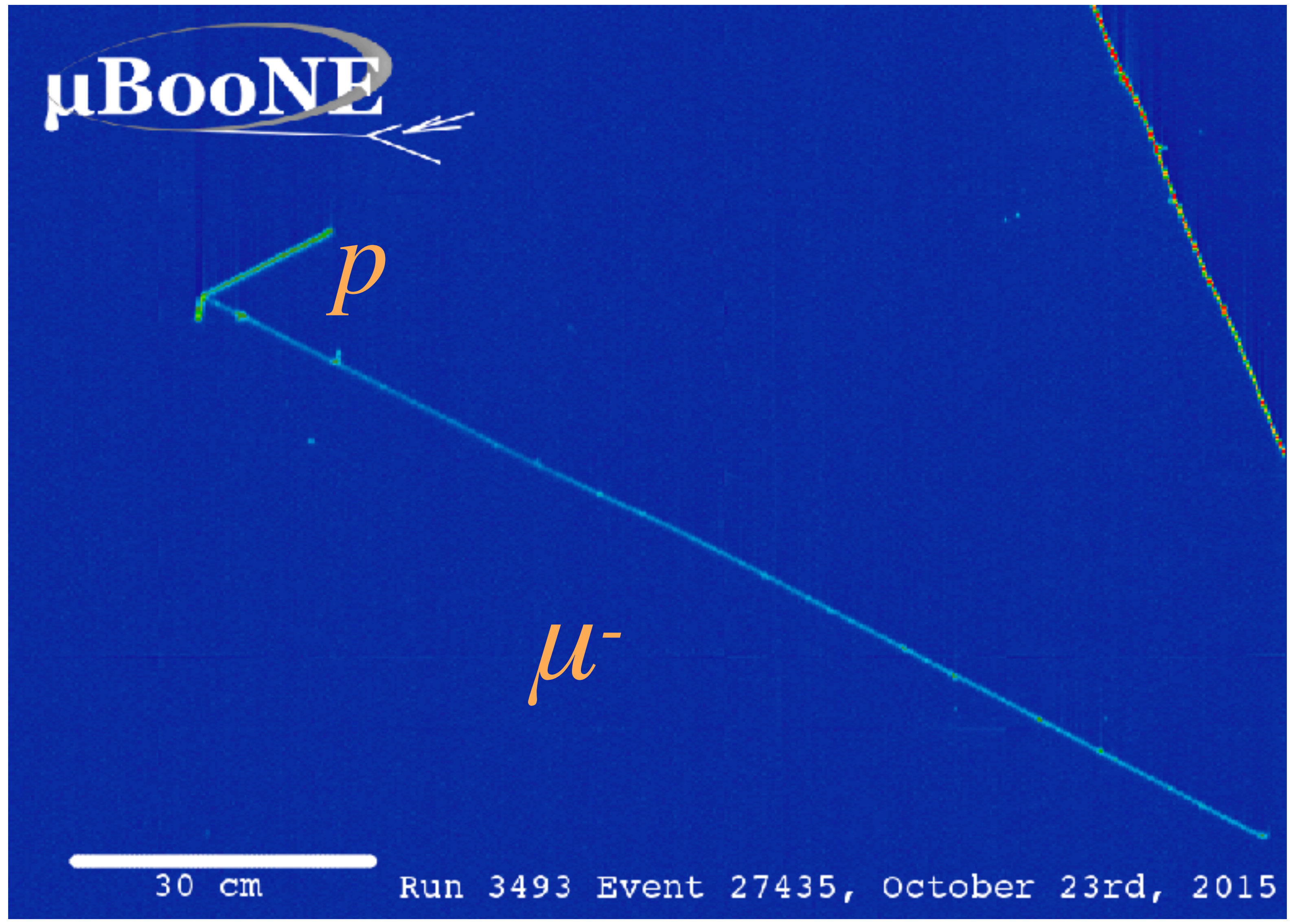
$$p^\mu_\mu = (E_\mu, (p_\mu \cos\theta_\mu), (p_\mu \sin\theta_\mu), 0)$$

$$p^\mu_p = (\sqrt{p_p^2 + m_p^2}, (p_p \cos\theta_p), (p_p \sin\theta_p), 0)$$

$$p^\mu_\nu = (E_\nu, E_\nu, 0, 0)$$

Charged-current quasi-elastic scattering - the “golden channel”





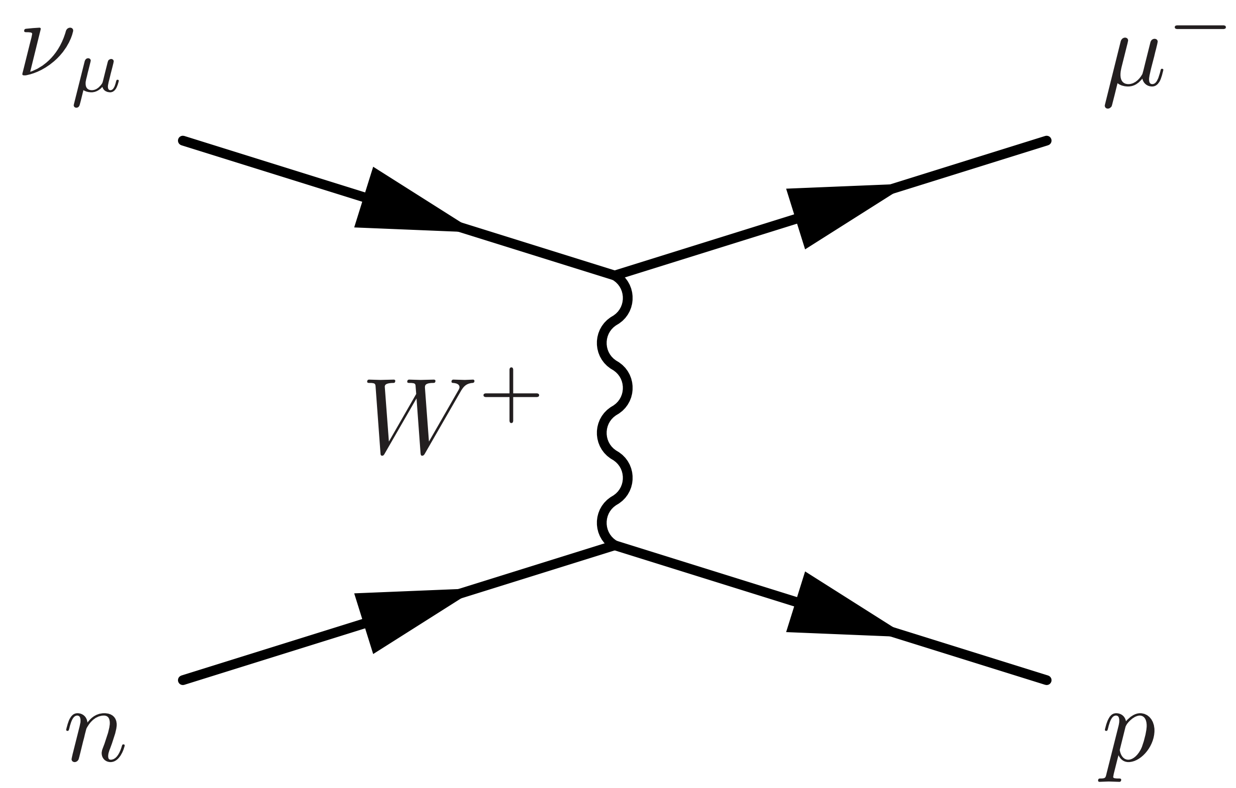
Simple final state - just a muon and a nucleon

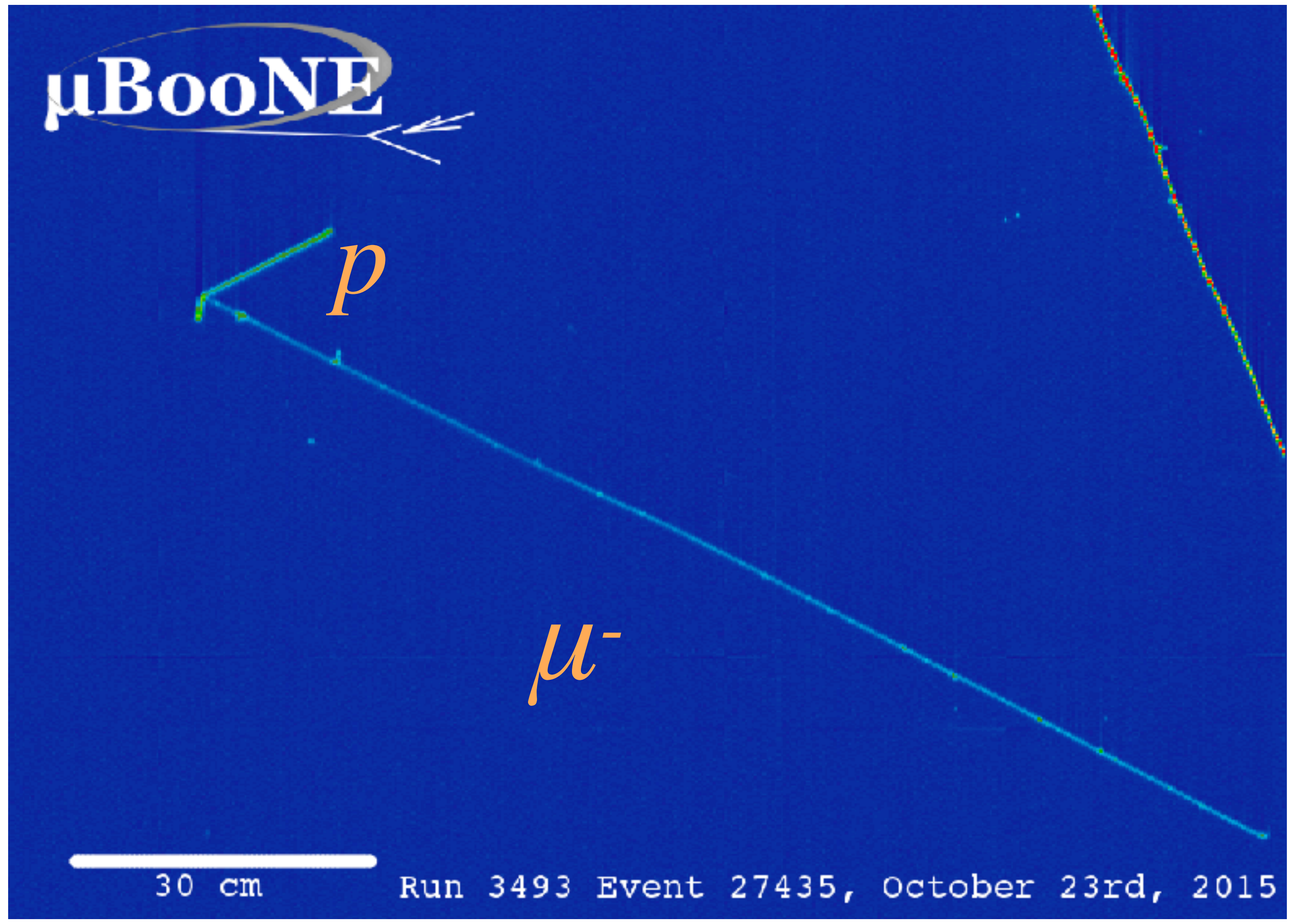
Conserve energy and momentum:
calculate Q^2 and E_ν just from muon kinematics

$$E_\nu^{\text{QE}} = \frac{m_p^2 - m_n^2 - m_\mu^2 + 2m_n E_\mu}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)}$$

Neutrino mode

Charged-current quasi-elastic scattering - the “golden channel”





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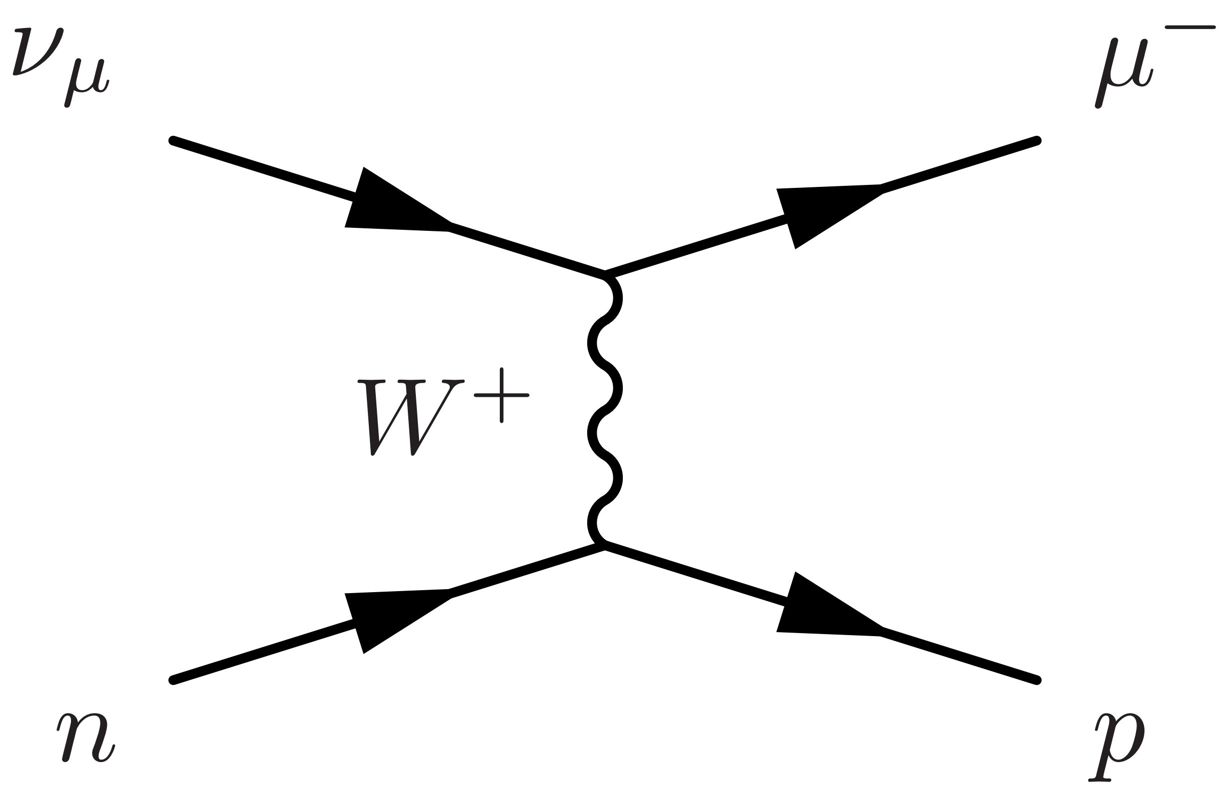
Neutrino mode

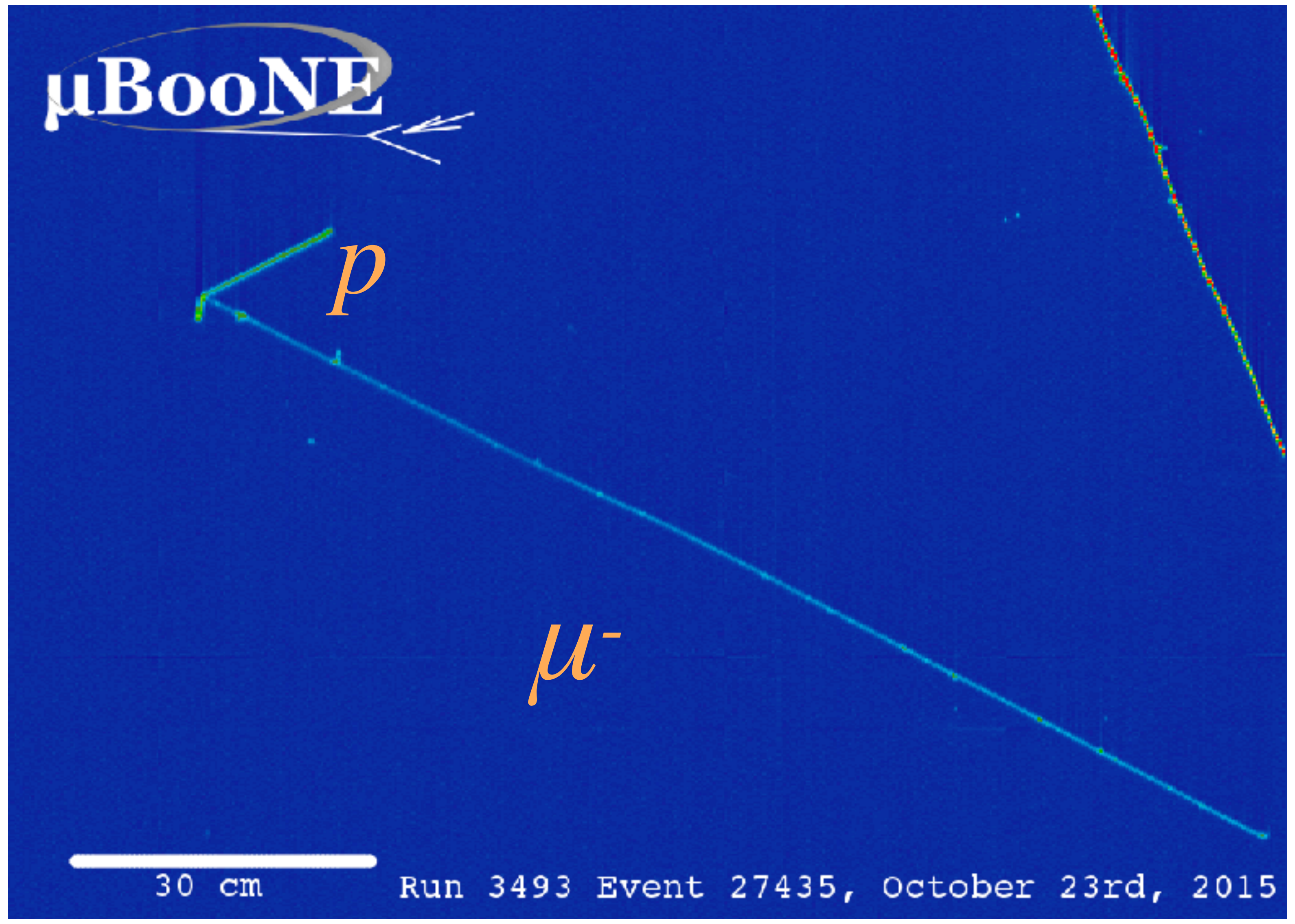
$$E_\nu^{\mathrm{QE}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

(in a nucleus; binding energy E_b = 28 MeV for argon)

Why is this useful?

Charged-current quasi-elastic scattering - the “golden channel”





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(in a nucleus; binding energy E_b = 28 MeV for argon)

Why is this useful?

- Muon has constant $\mathrm{d}E/\mathrm{d}x$ (minimum-ionizing particle)
- Long, clear track: **easy to measure E_μ and θ_μ**
- $\bar{\nu}$ case - neutron hard to detect (neutral)
- Not affected by **final-state interactions**
  - Nucleons can re-interact in the nucleus. *We will come back to this!*

Want to know more? Join the hands-on activity on June 21!

Charged-current quasi-elastic cross section

For free nucleons, the CCQE cross section is well understood (this is the simple one?!)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}_{\mathrm{QE}}\binom{\nu_l n \to l^- p}{\bar{\nu}_l p \to l^+ n} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left\{A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)

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Cabibbo angle
Fermi constant

} Weak interaction: small cross section

Nucleon mass

C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)

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Neutrino energy

ν and $\bar{\nu}$ cross sections different
($\sigma_\nu \cong 3\ \sigma_{\bar{\nu}}$)

Mandelstam variables

C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)

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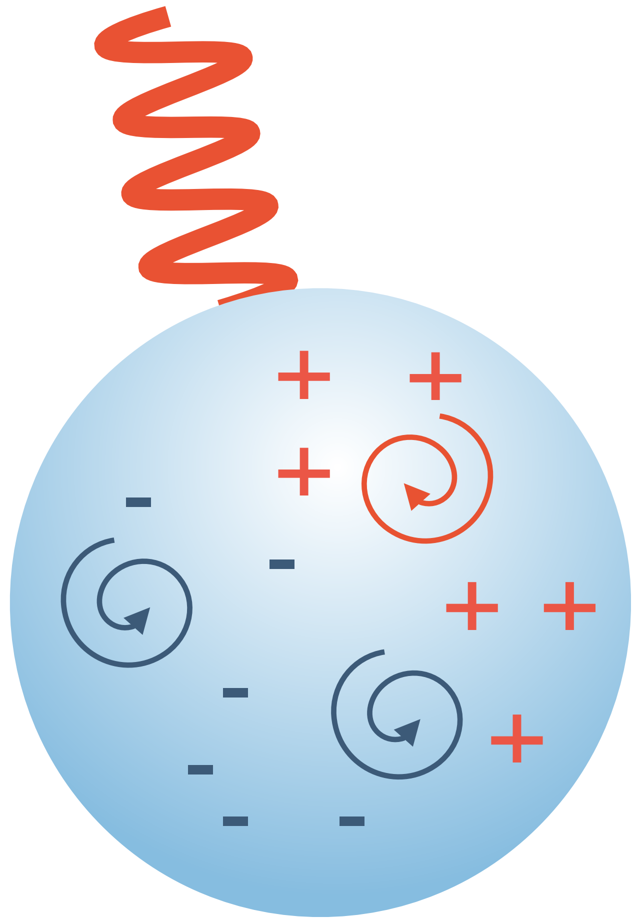
$$\begin{aligned}A(Q^2) = \frac{m_l^2+Q^2}{M^2}\Bigg\{&\left(1+\frac{Q^2}{4M^2}\right)|F_A|^2-\left(1-\frac{Q^2}{4M^2}\right)F_1^2\\&+\frac{Q^2}{4M^2}\left(1-\frac{Q^2}{4M^2}\right)(\xi F_2)^2+\frac{Q^2}{M^2}Re(F_1^*\xi F_2)-\frac{Q^2}{M^2}\left(1+\frac{Q^2}{4M^2}\right)(F_A^3)^2\\&-\frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2+|F_A+2F_P|^2-4\left(1+\frac{Q^2}{4M^2}\right)((F_V^3)^2+F_P^2)\right]\Bigg\}\end{aligned}$$

$$B(Q^2)=\frac{Q^2}{M^2}Re\left[F_A^*(F_1+\xi F_2)\right]-\frac{m_l^2}{M^2}Re\left[(F_1-\tau\xi F_2)F_V^{3*}-(F_A^*-\frac{Q^2}{2M^2}F_P)F_A^3)\right]$$

$$C(Q^2)=\frac{1}{4}\left\{F_A^2+F_1^2+\tau(\xi F_2)^2+\frac{Q^2}{M^2}(F_A^3)^2\right\}$$

Free nucleon form factors (functions of Q^2)

Vector form factors



Functions of electric & magnetic form factors, describing charge and current distributions in the nucleon

At $Q^2 = 0$, these simplify to the charge and magnetic moment

Measured using electron scattering

C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)

Charged-current quasi-elastic cross section

For free nucleons, the CCQE cross section is well understood (this is the simple one?!)

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$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

Free nucleon form factors (functions of Q^2)

F^3 form factors: thankfully, negligible

F_P (**pseudoscalar** form factor): related to other factors

C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)

Charged-current quasi-elastic cross section

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$$\begin{aligned}A(Q^2) = \frac{m_l^2+Q^2}{M^2}\Bigg\{&\left(1+\frac{Q^2}{4M^2}\right)|F_A|^2 - (1-\frac{Q^2}{4M^2})F_1^2 \\ &+ \frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2})(\xi F_2)^2 + \frac{Q^2}{M^2}Re(F_1^*\xi F_2) - \frac{Q^2}{M^2}(1+\frac{Q^2}{4M^2})(F_A^3)^2 \\ &- \frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2 + |F_A + 2F_P|^2 - 4(1+\frac{Q^2}{4M^2})((F_V^3)^2+F_P^2)\right]\Bigg\}\end{aligned}$$

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$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

Free nucleon form factors (functions of Q^2)

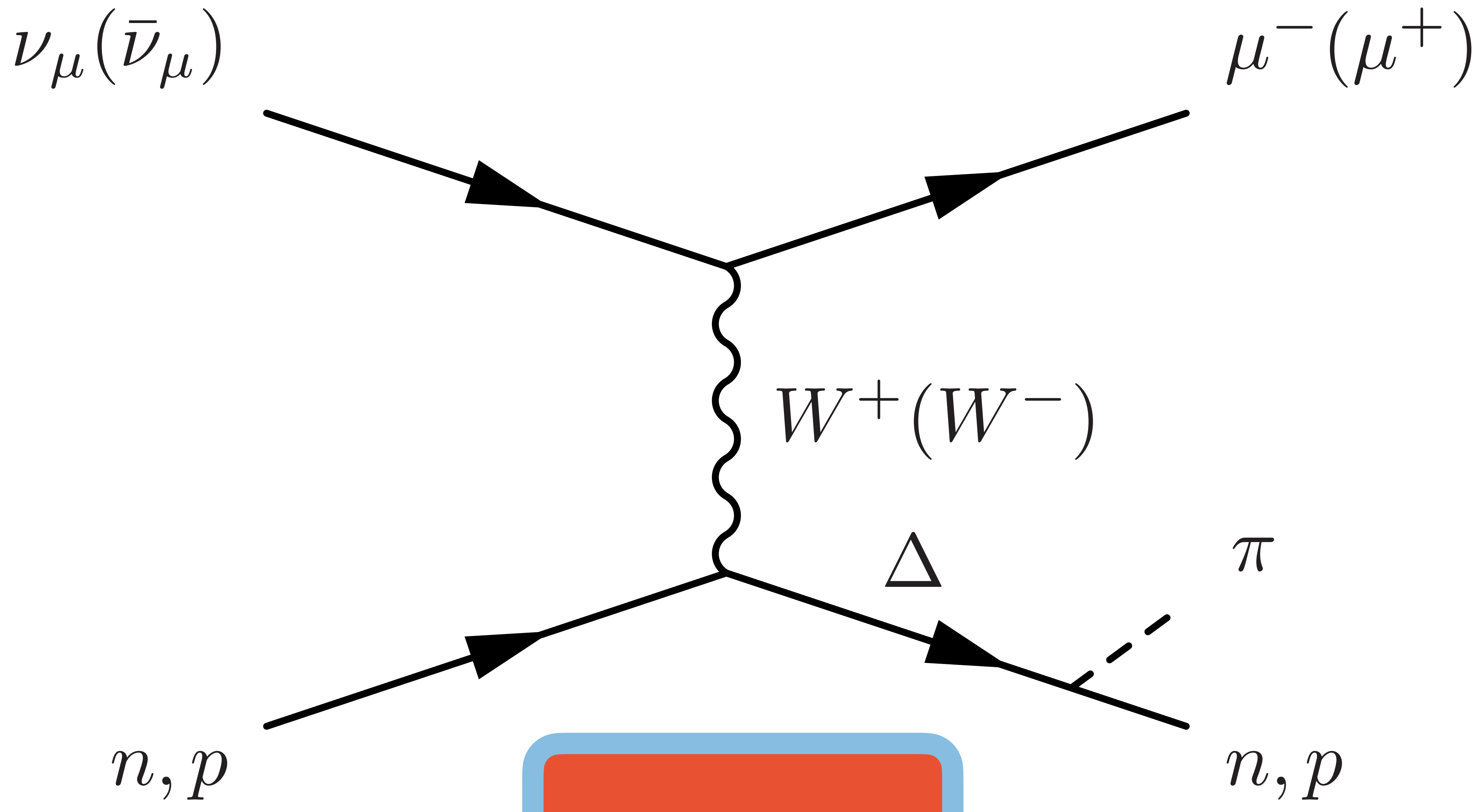
Axial form factor

Only accessible through weak processes (V-A current) i.e. processes with **neutrinos**

$F_A(Q^2)$ is still being studied, and is not fully understood for heavy nuclei

C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)

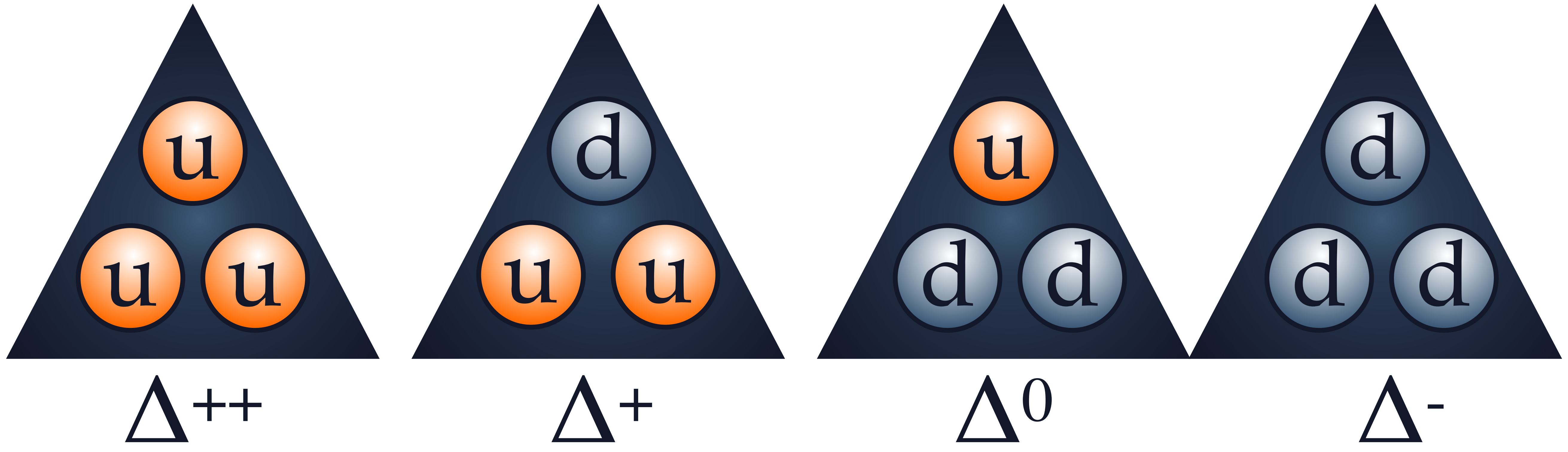
Resonant pion production



Exercise 5

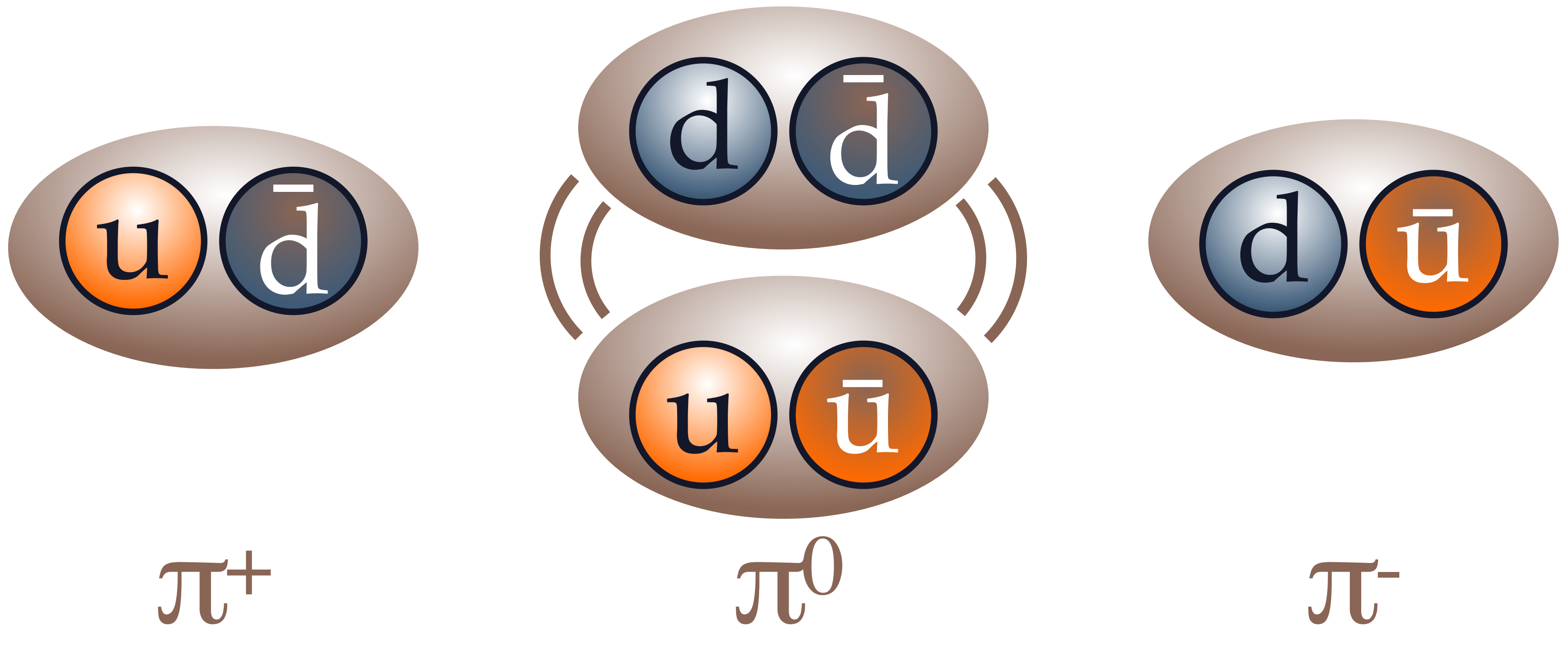
Both neutrinos and antineutrinos can scatter from both neutrons and protons.
Some Δ resonances have multiple decay modes.
Can you write the equations for all ν and $\bar{\nu}$ possibilities? (Hint, 3 for each… conserve charge)

Δ resonances (mass 1232 MeV) are excited-state baryons (spin 3/2)

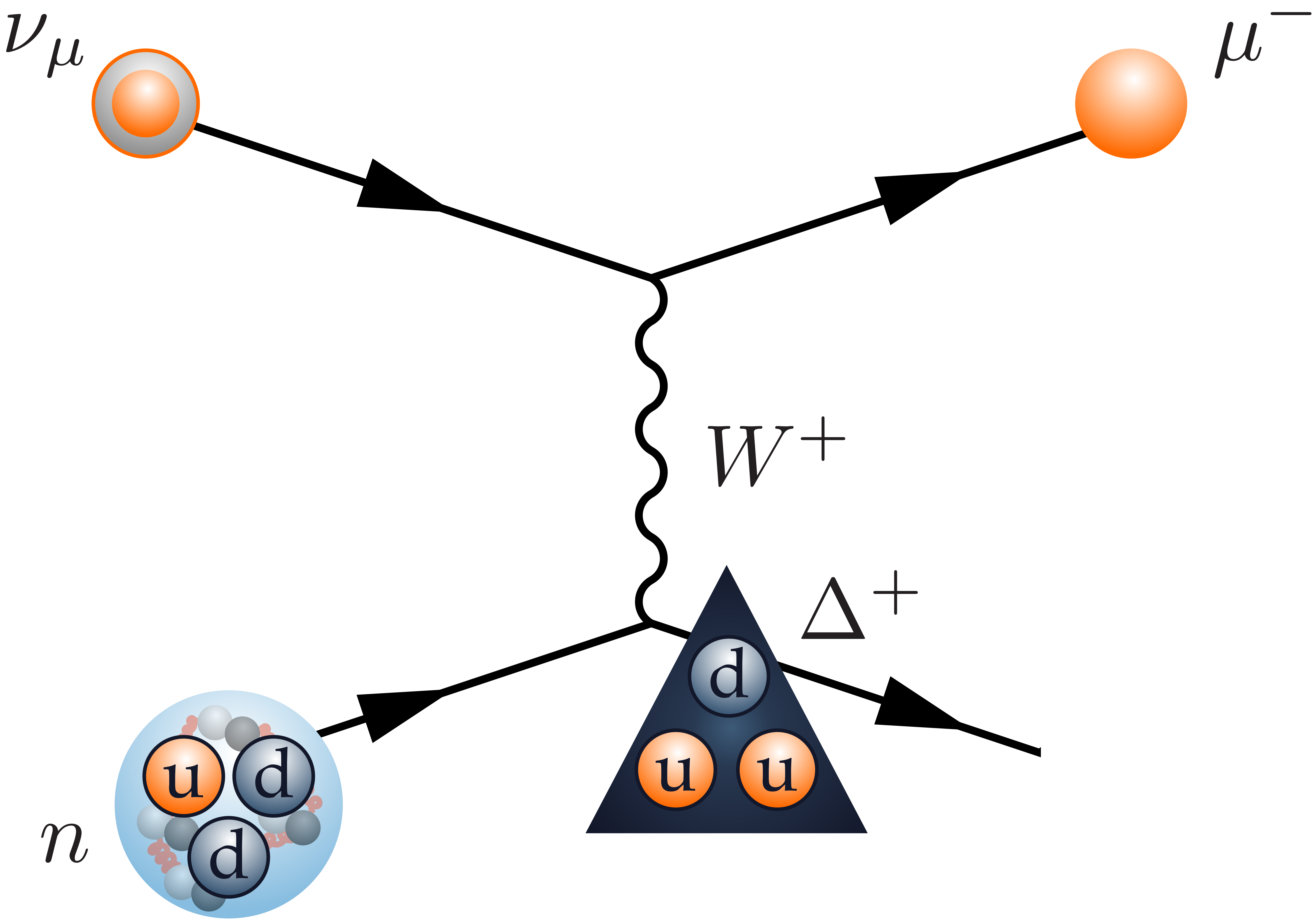


(Heavier resonances also exist)

Pions are mesons (spin 0)

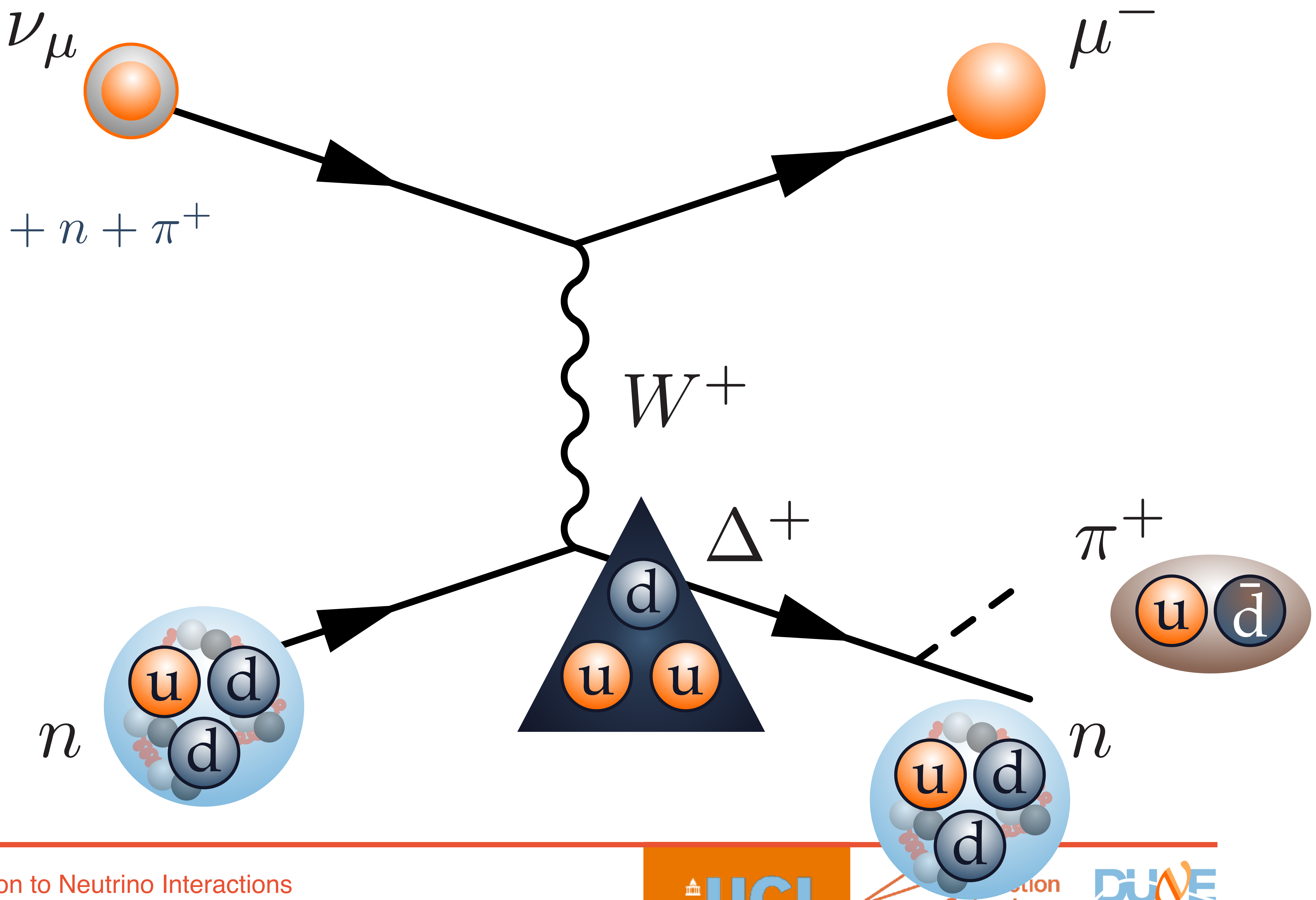


As easy as π ?



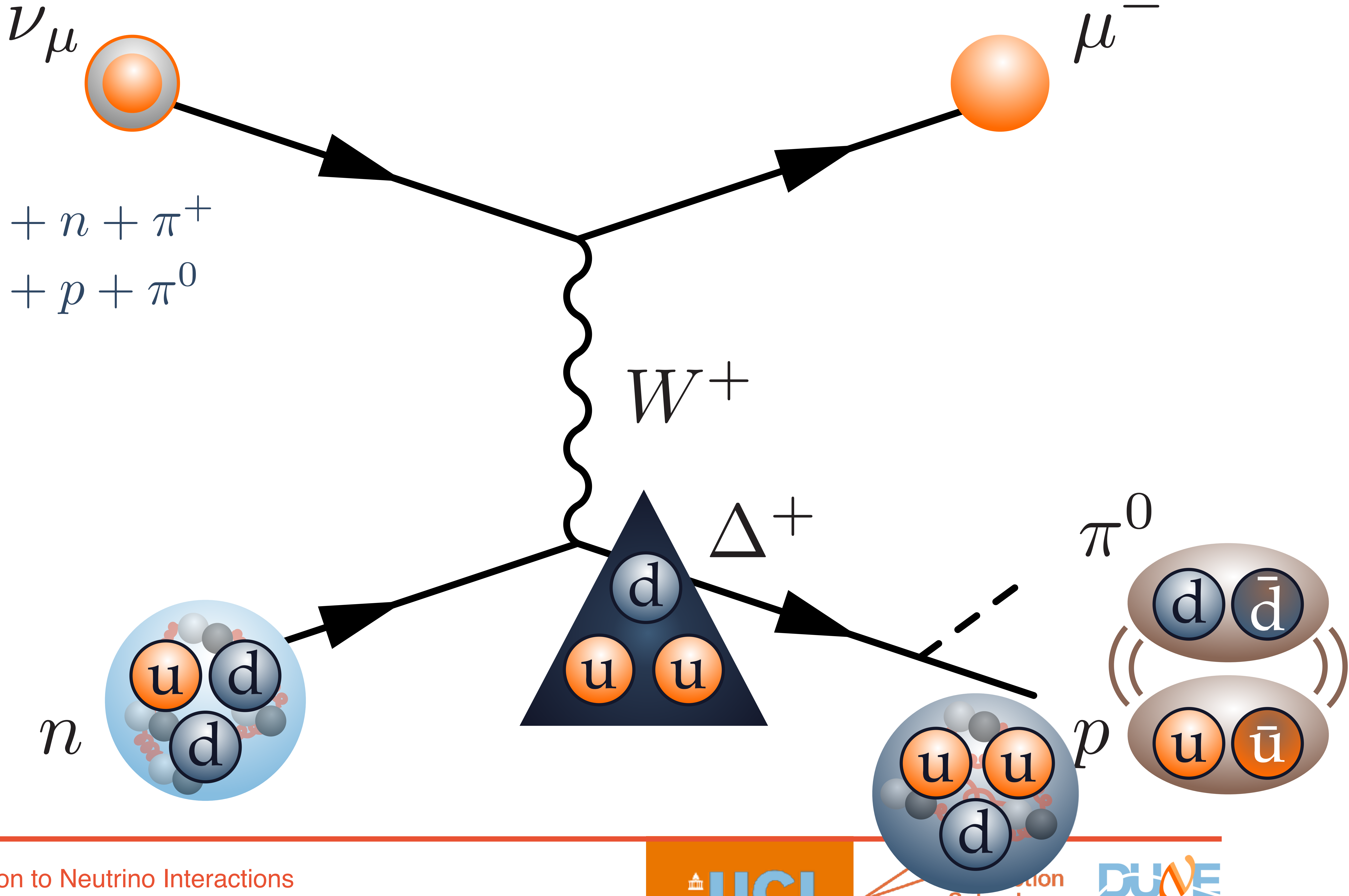
As easy as π ?

$$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + n + \pi^+$$



As easy as π ?

$$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + n + \pi^+$$
$$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + p + \pi^0$$



Lots of options…

Neutrino mode

$$\nu_\mu + n \to \mu^- + \Delta^+ \to \mu^- + n + \pi^+$$

$$\nu_\mu + n \to \mu^- + \Delta^+ \to \mu^- + p + \pi^0$$

$$\nu_\mu + p \to \mu^- + \Delta^{++} \to \mu^- + p + \pi^+$$

Antineutrino mode

$$\bar{\nu}_\mu + p \to \mu^+ + \Delta^0 \to \mu^+ + p + \pi^-$$

$$\bar{\nu}_\mu + p \to \mu^+ + \Delta^0 \to \mu^+ + n + \pi^0$$

$$\bar{\nu}_\mu + n \to \mu^+ + \Delta^- \to \mu^+ + n + \pi^-$$

Lots of options…

Neutrino mode

$$\nu_\mu + n \to \mu^- + \Delta^+ \to \mu^- + n + \pi^+$$

$$\nu_\mu + n \to \mu^- + \Delta^+ \to \mu^- + p + \pi^0$$

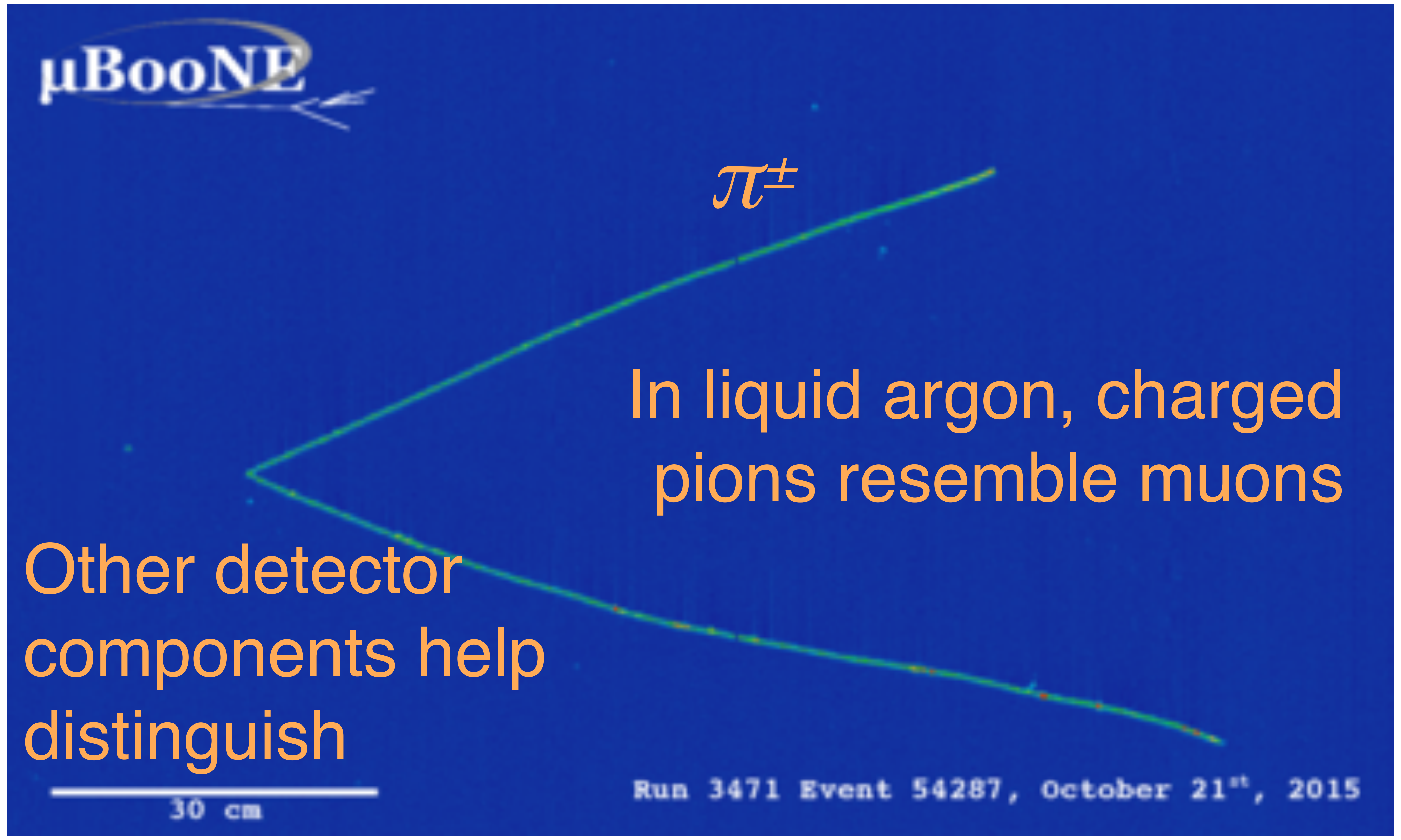
$$\nu_\mu + p \to \mu^- + \Delta^{++} \to \mu^- + p + \pi^+$$

Antineutrino mode

$$\bar{\nu}_\mu + p \to \mu^+ + \Delta^0 \to \mu^+ + p + \pi^-$$

$$\bar{\nu}_\mu + p \to \mu^+ + \Delta^0 \to \mu^+ + n + \pi^0$$

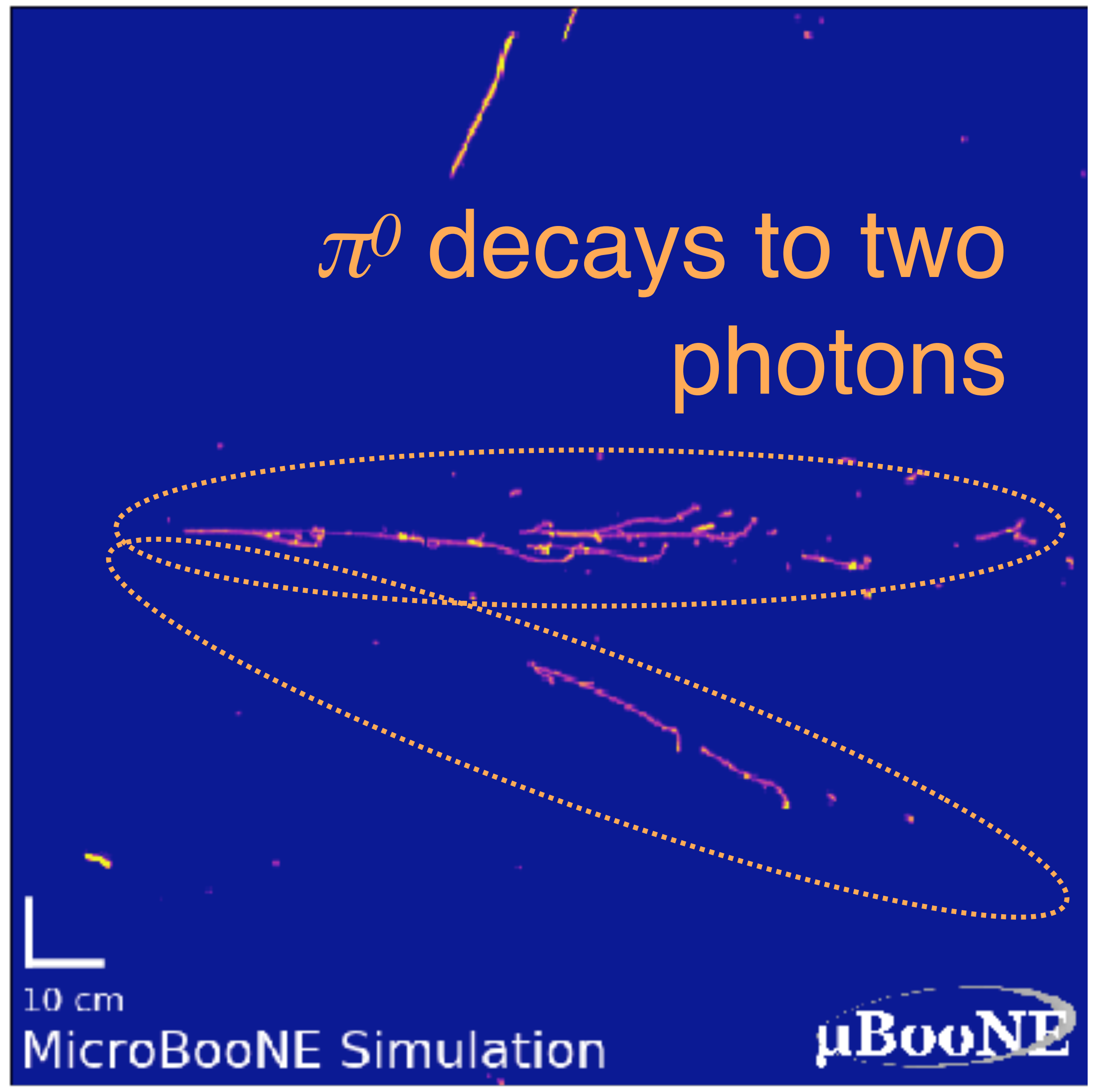
$$\bar{\nu}_\mu + n \to \mu^+ + \Delta^- \to \mu^+ + n + \pi^-$$



In liquid argon, charged pions resemble muons

Other detector components help distinguish

All pions can be detected, but finding the direction is harder for π^0

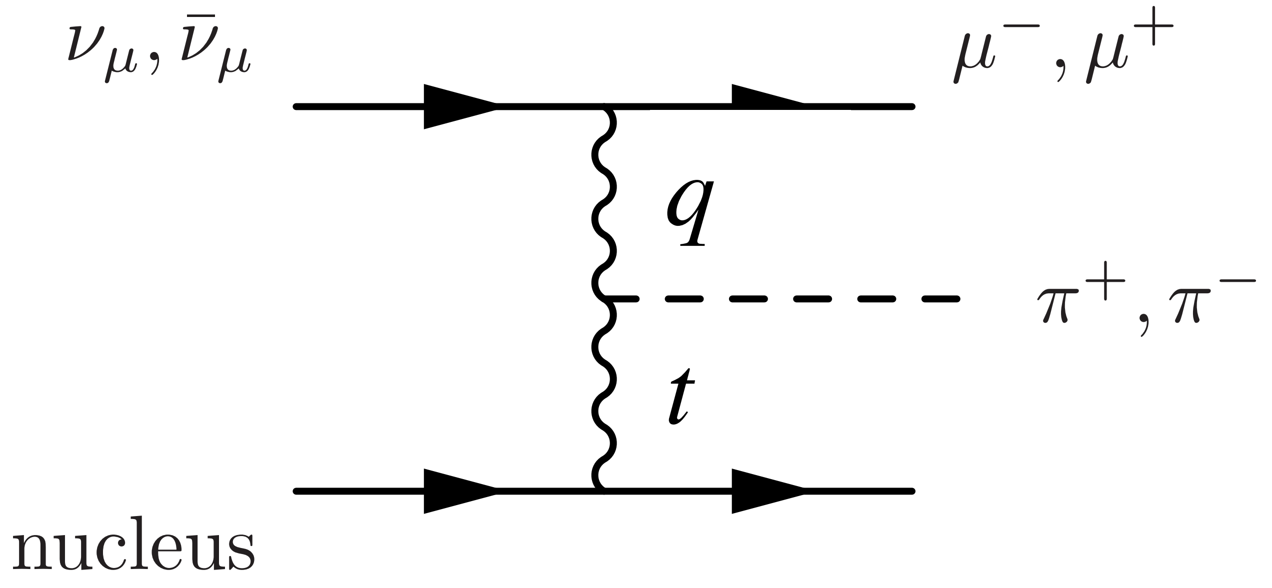


π^0 decays to two photons

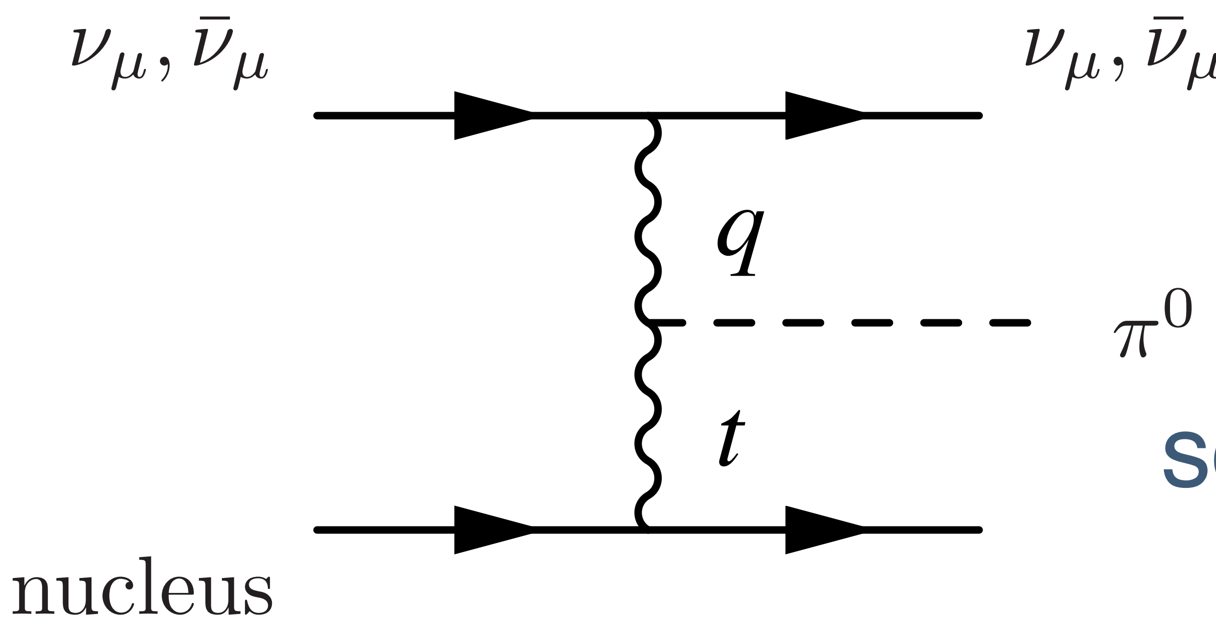
More recipes for π

Coherent pion production

For very low four-momentum transfer t, a neutrino can scatter from the **nucleus**, leaving it in its ground state



Charged-current scattering makes a π±

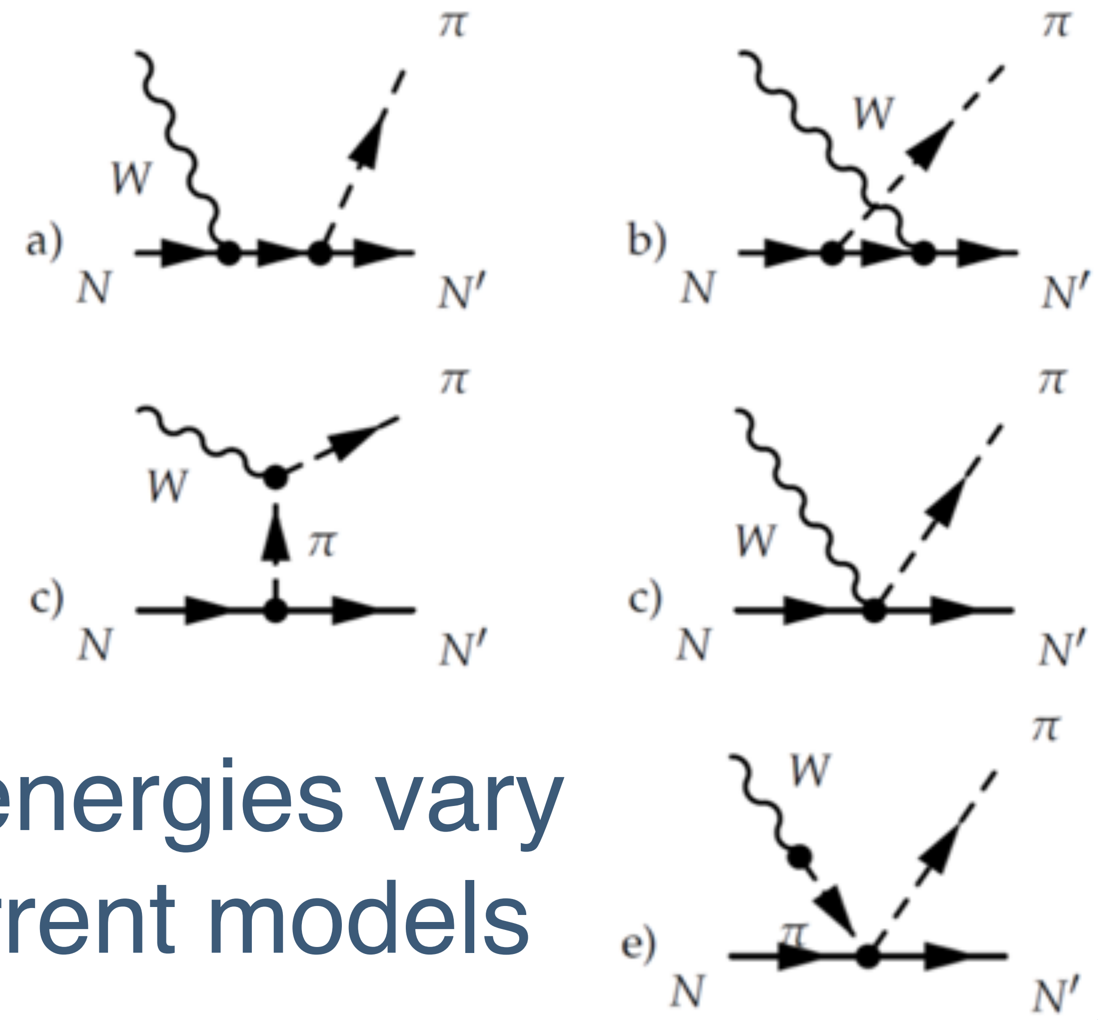


Neutral-current scattering makes a π^0

Non-resonant pion production

Various other processes can produce final-state pions.

Phys. Rev. D 97, 013002 (2018)

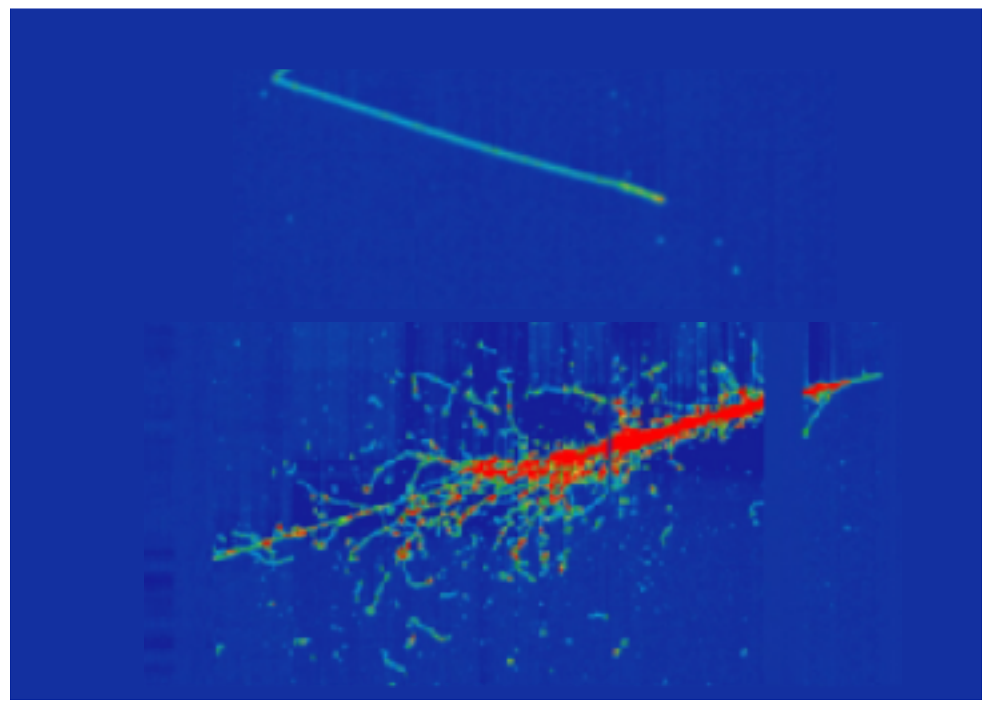


Predicted pion counts / energies vary significantly between current models

The neutral-current problem

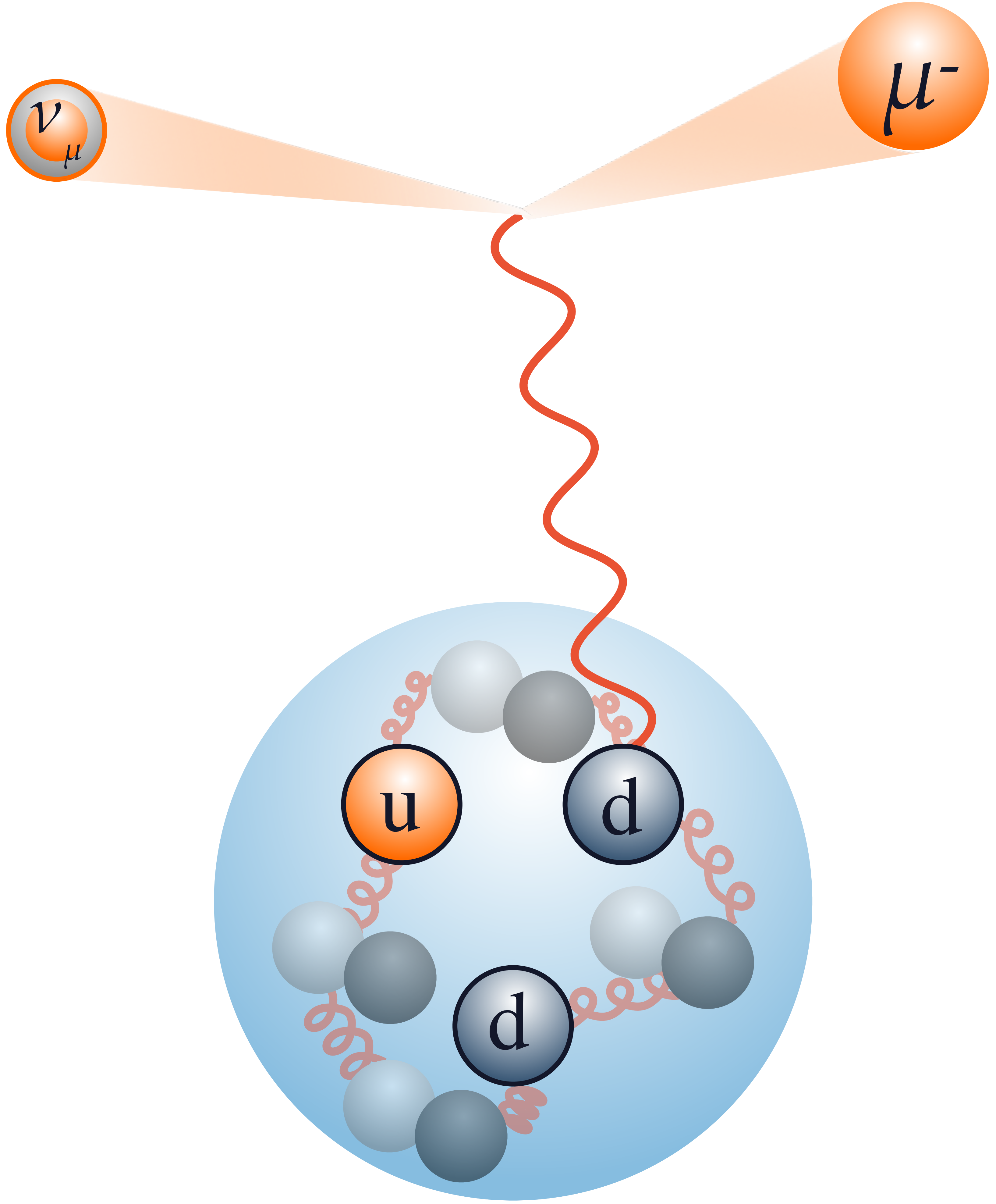
ν (invisible) + π±
can look like μ±

ν + π^0 (→γγ)
can look like e±



Deep Inelastic Scattering (DIS)

Question 2

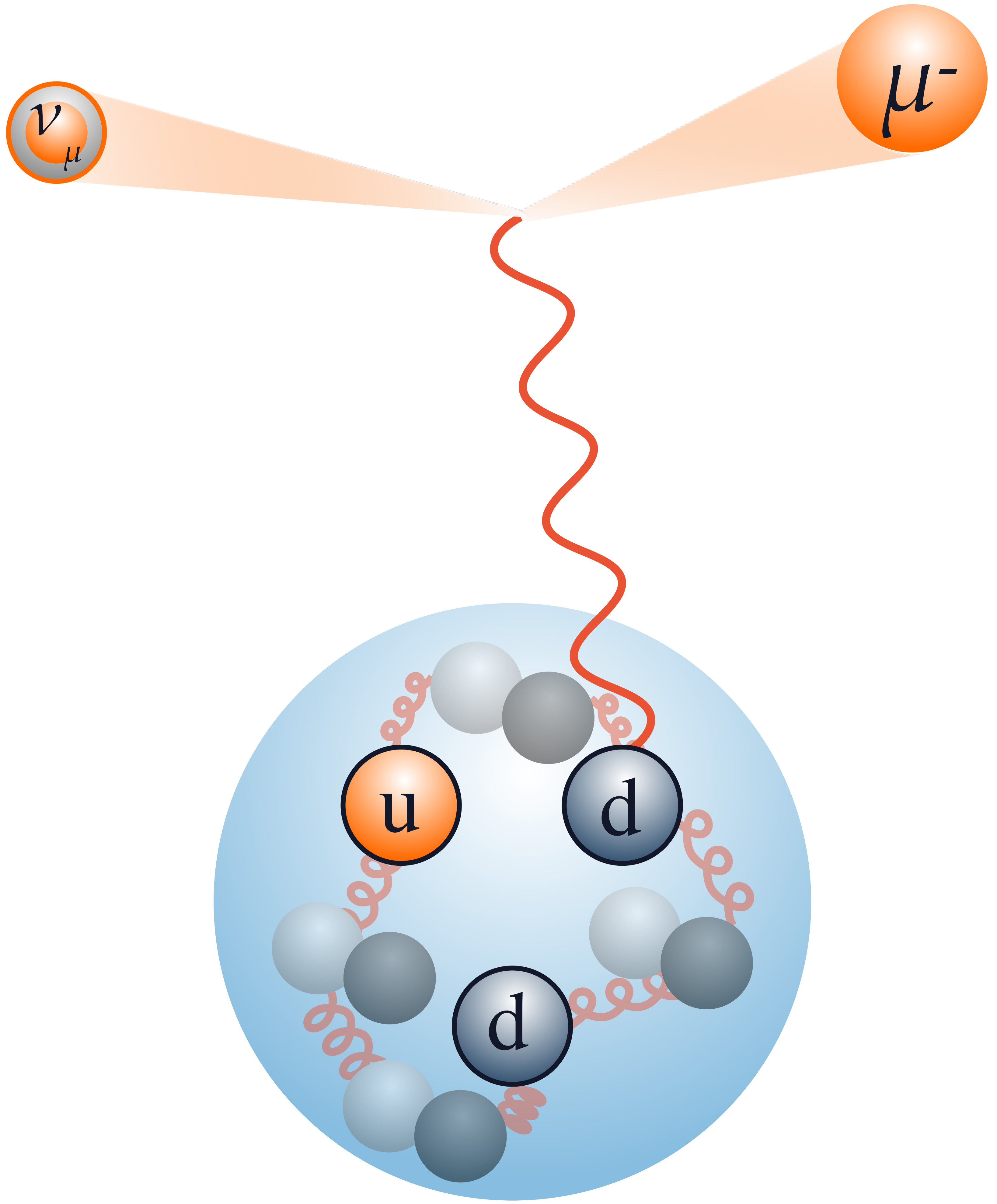


- Neutrinos with high enough energy can scatter from an **individual quark** (valence or sea)

Which quarks / antiquarks do neutrinos and antineutrinos interact with?
u, $\bar{u}$, d, $\bar{d}$, s, $\bar{s}$, c,$\bar{c}$

Deep Inelastic Scattering (DIS)

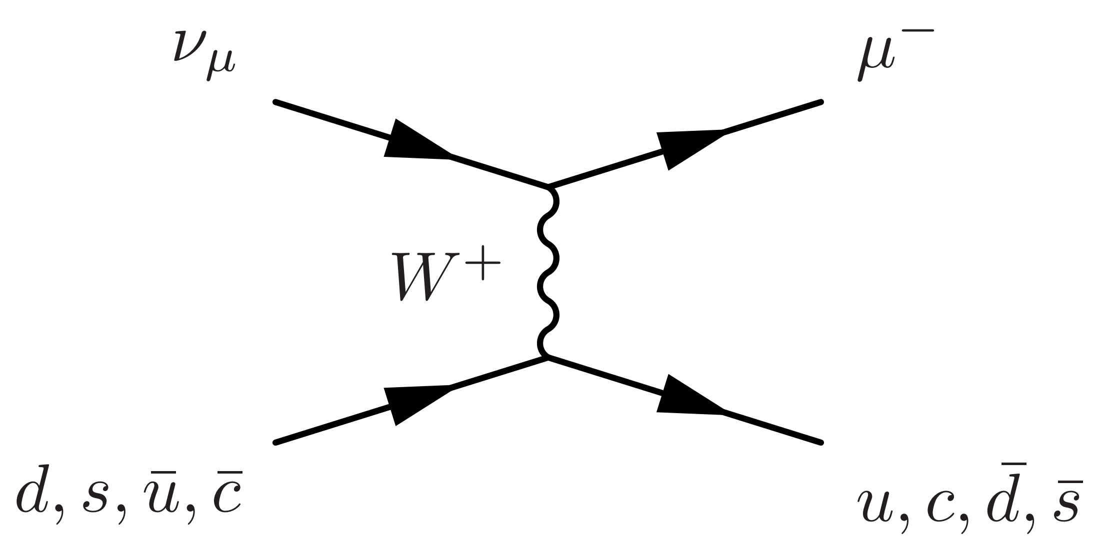
Question 2



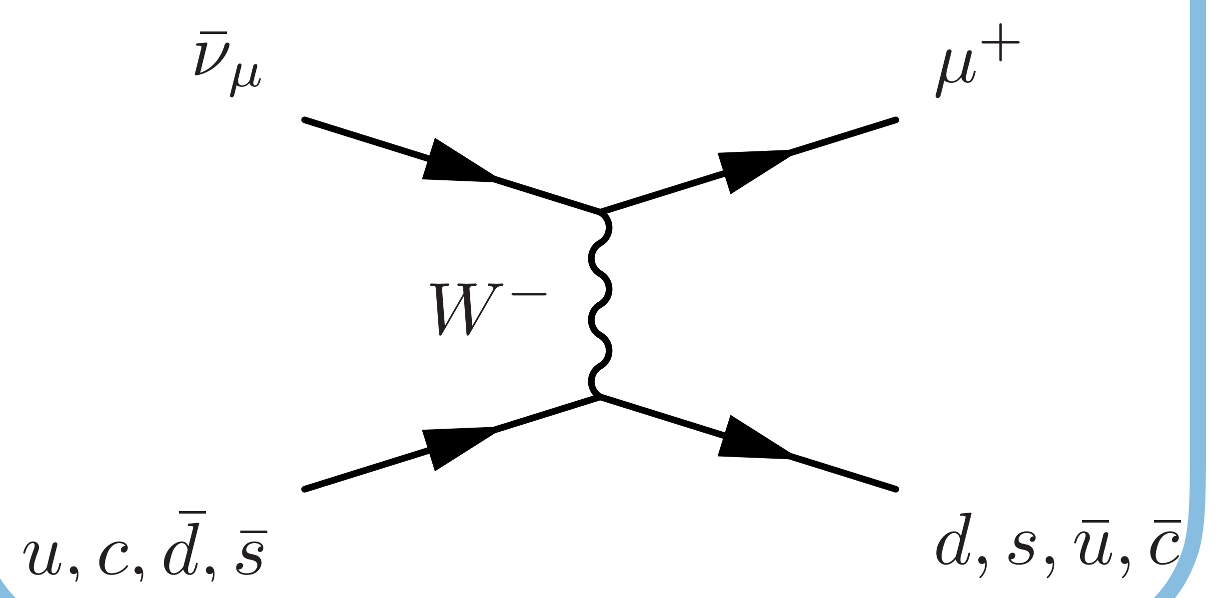
- Neutrinos with high enough energy can scatter from an **individual quark** (valence or sea)

Which quarks / antiquarks do neutrinos and antineutrinos interact with?
u, ū, d, d̄, s, s̄, c,c̄

Neutrino mode

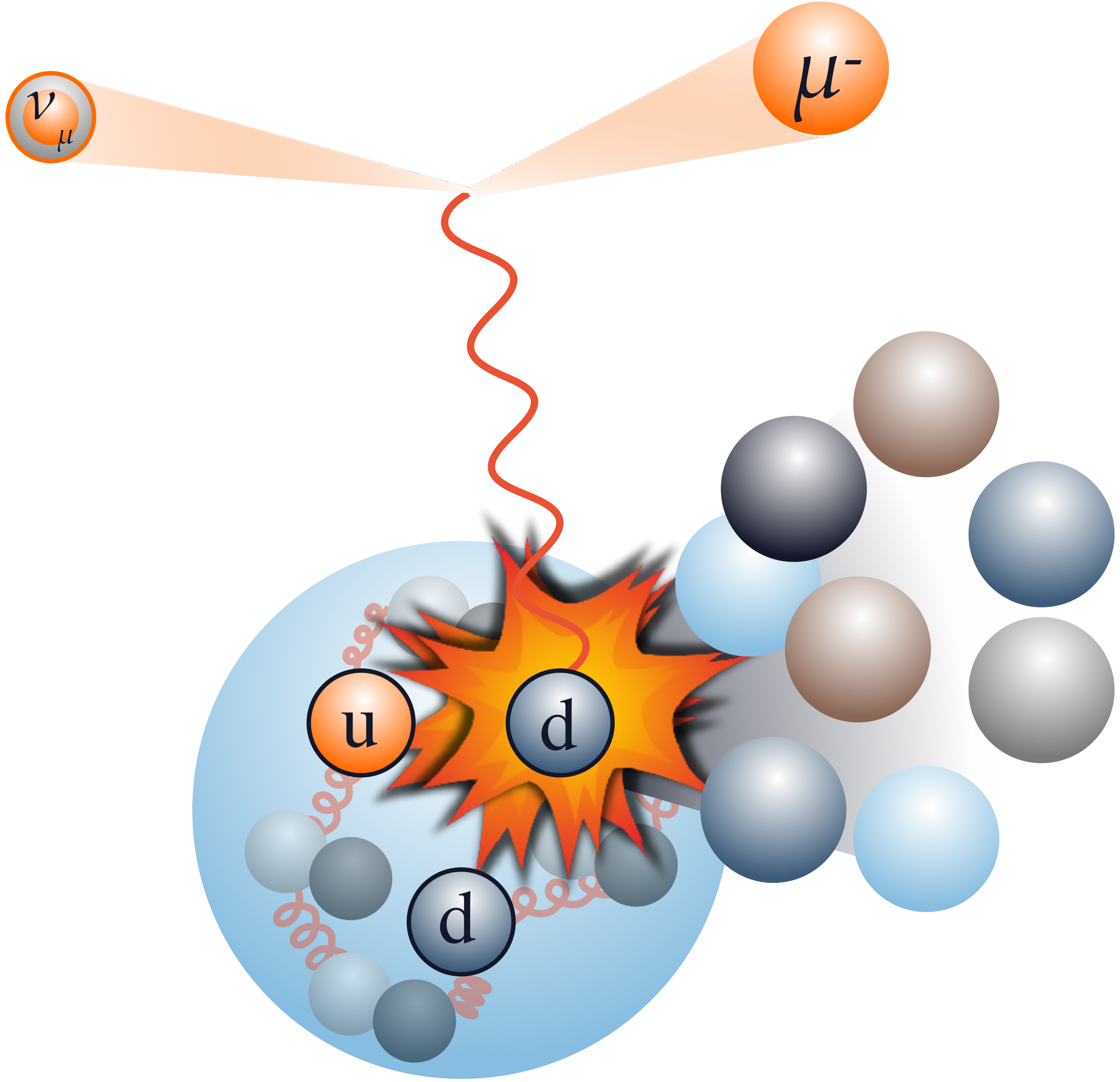


Antineutrino mode



Deep Inelastic Scattering (DIS)

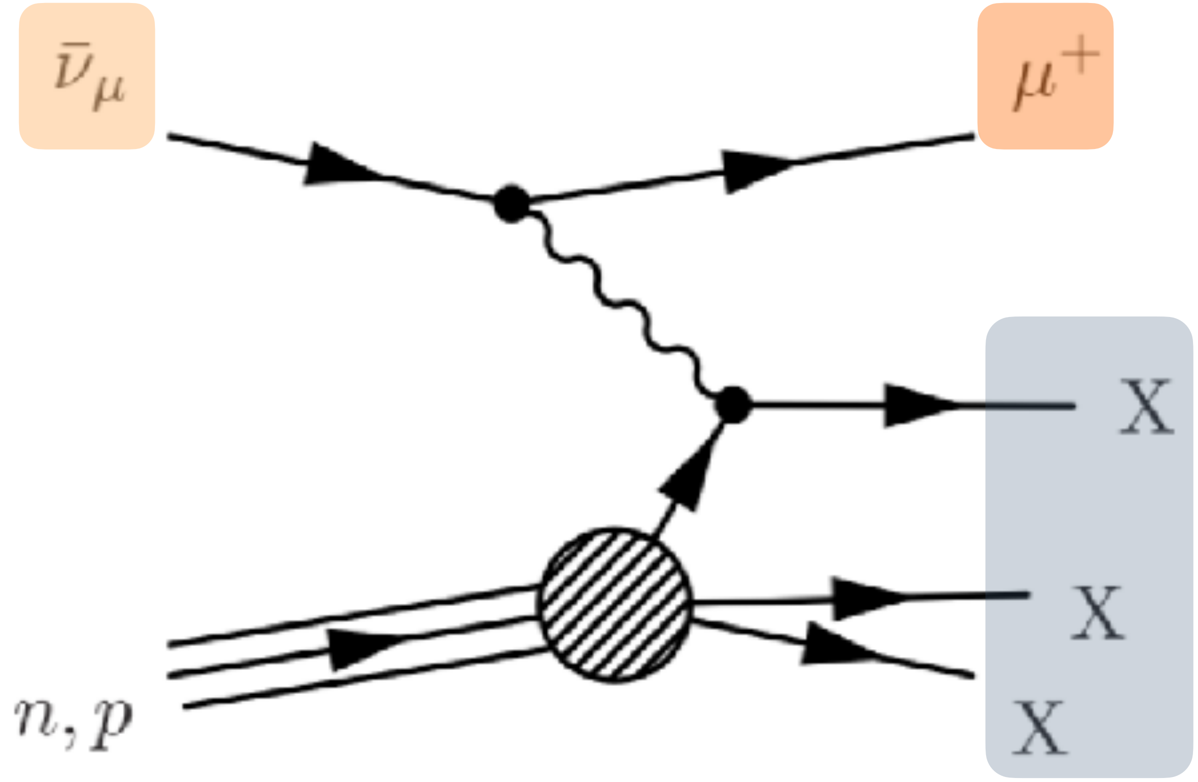
Question 2



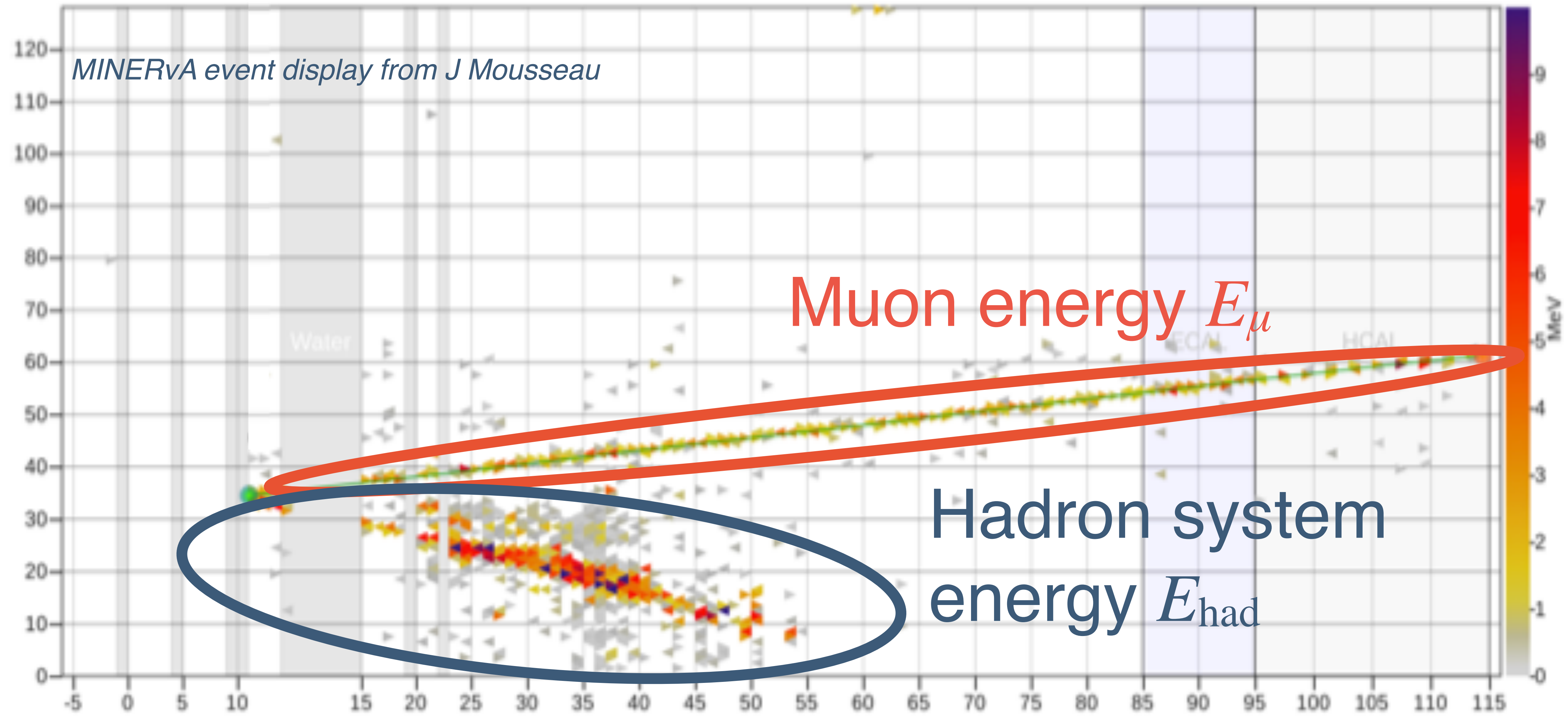
- Neutrinos with high enough energy can scatter from an **individual quark** (valence or sea)
- The knocked-out quark can't exist alone
- It **hadronizes** to produce a hadron shower

Studying DIS interactions

Rather than trying to resolve individual particles, sum the **energy of the hadron system**



$$E_\nu = E_\mu + E_{\text{had}}$$



Muon energy E_μ

Hadron system energy E_{had}

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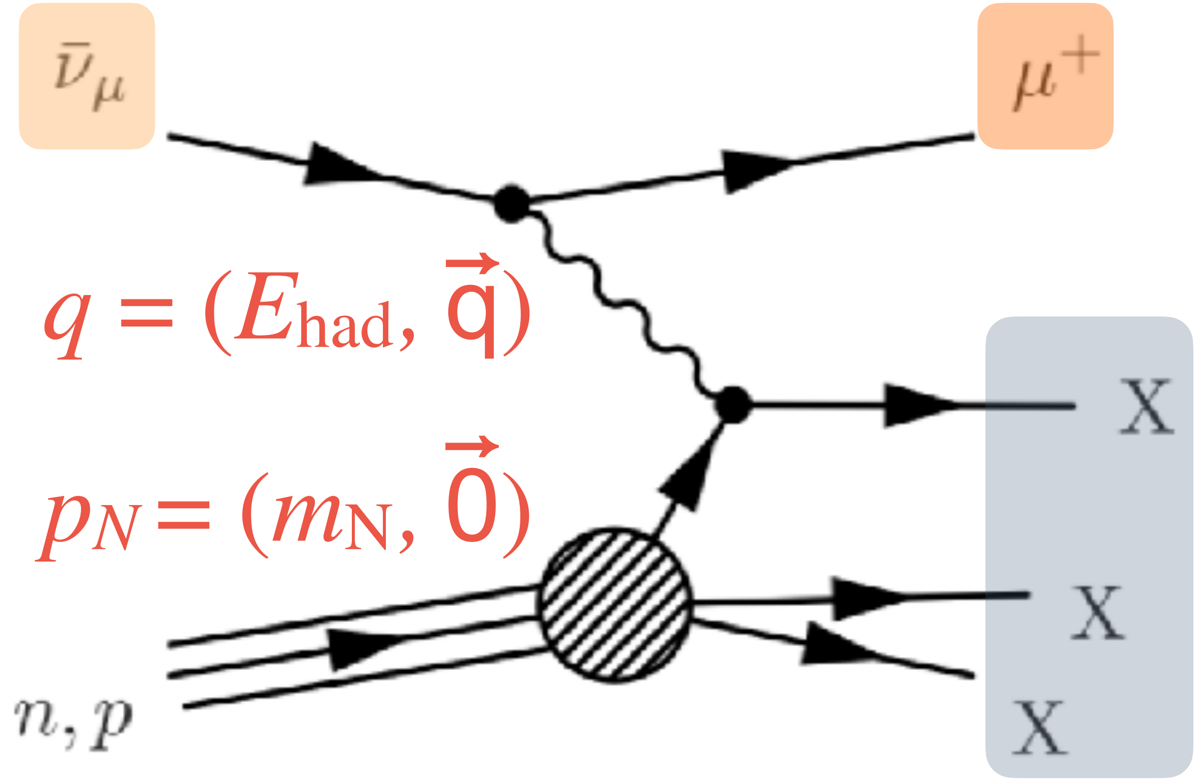

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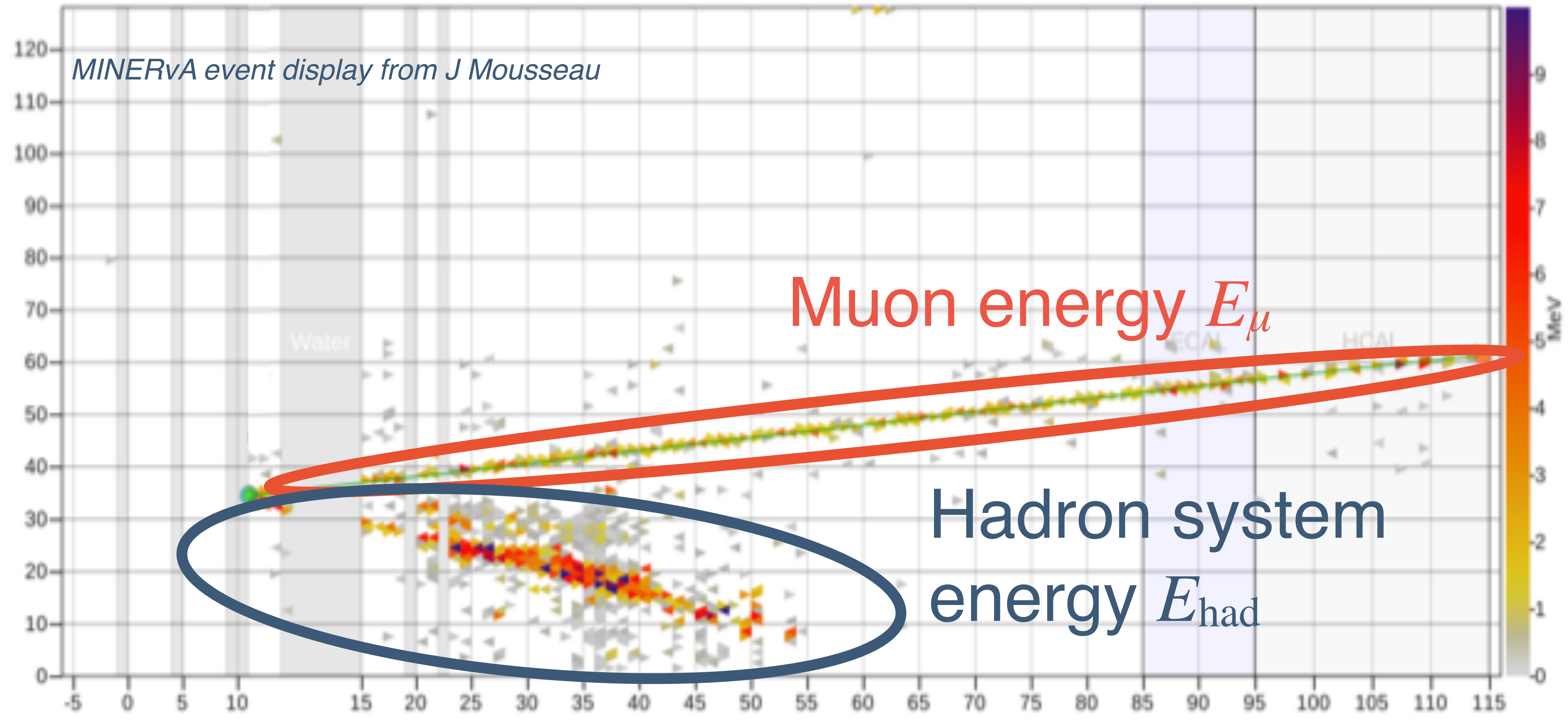


MINERvA event display from J Mousseau

Muon energy E_μ

Hadron system energy E_{had}

Other useful variables

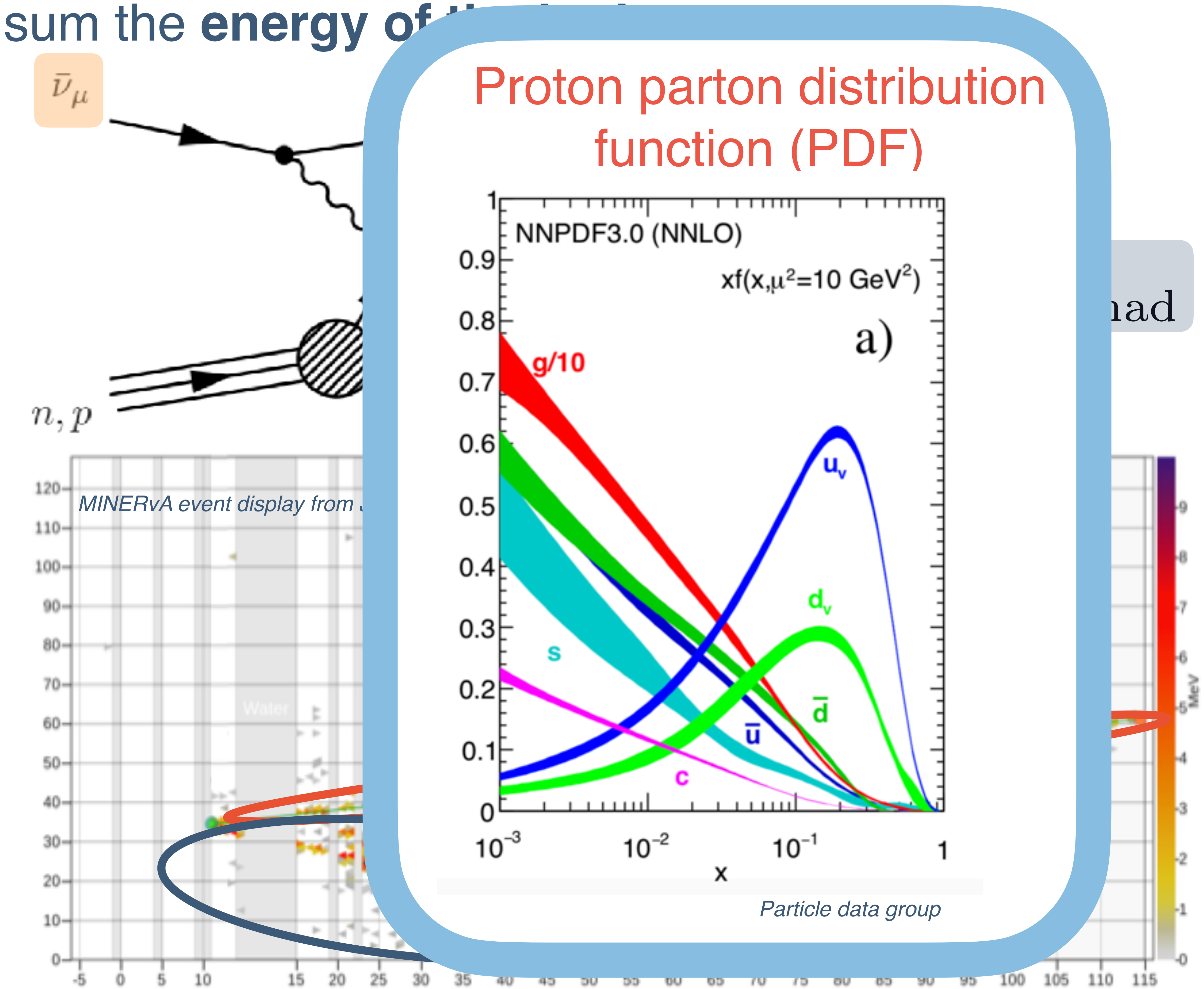
Invariant mass W of final-state hadronic system

$$\begin{aligned} W^2 &= (q + p_N)^2 \\ &= q^2 + p_N^2 + 2q.p_N \\ &= m_N^2 - Q^2 + 2m_N E_{\text{had}} \end{aligned}$$

For DIS, W is typically > 2GeV

Studying DIS interactions

Rather than trying to resolve individual particles, sum the **energy of**



Proton parton distribution function (PDF)

Particle data group

Other useful variables

Invariant mass W of final-state hadronic system

$$W^2 = m_N^2 - Q^2 + 2m_N E_{\text{had}}$$

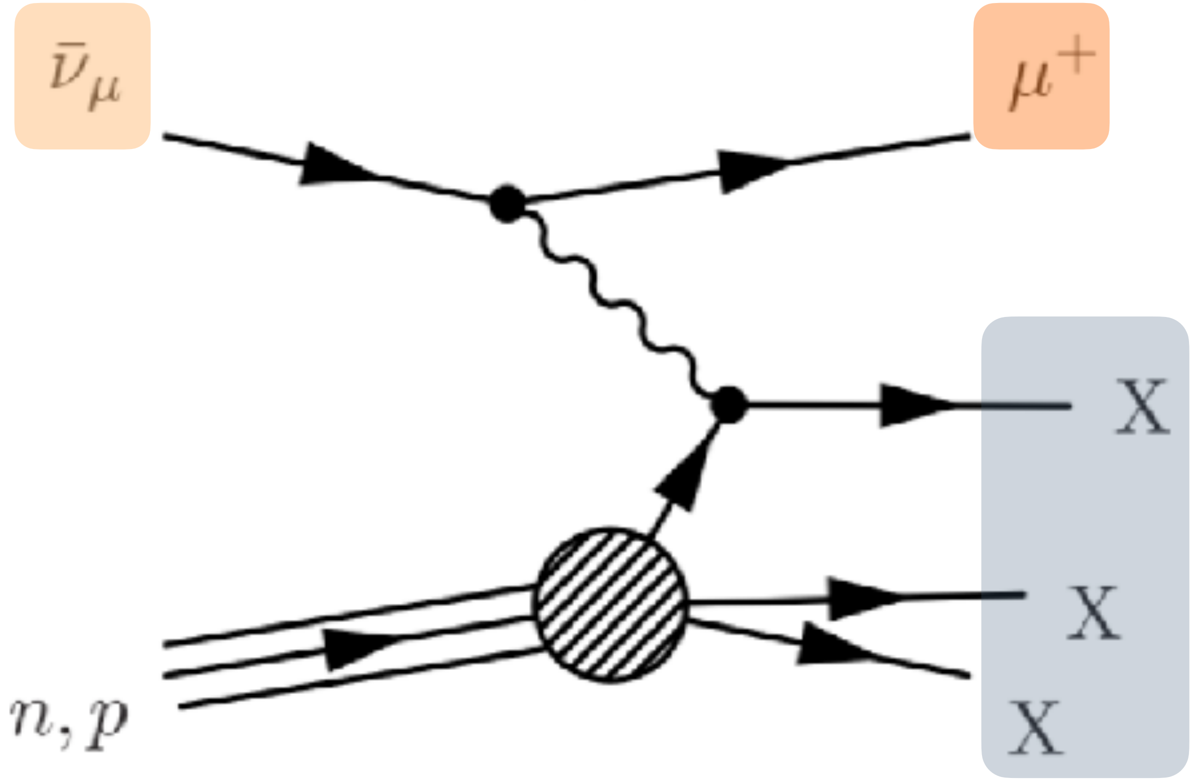
Bjorken scaling variable x is the fraction of momentum carried by the struck quark

$$x = \frac{Q^2}{2m_N E_{\text{had}}}$$

- For DIS, $0 < x < 1$
- Valence quarks have bigger x than sea quarks
- What are W and x for a CCQE interaction (whole nucleon knocked out)?

Studying DIS interactions

Rather than trying to resolve individual particles, sum the **energy of the hadron system**



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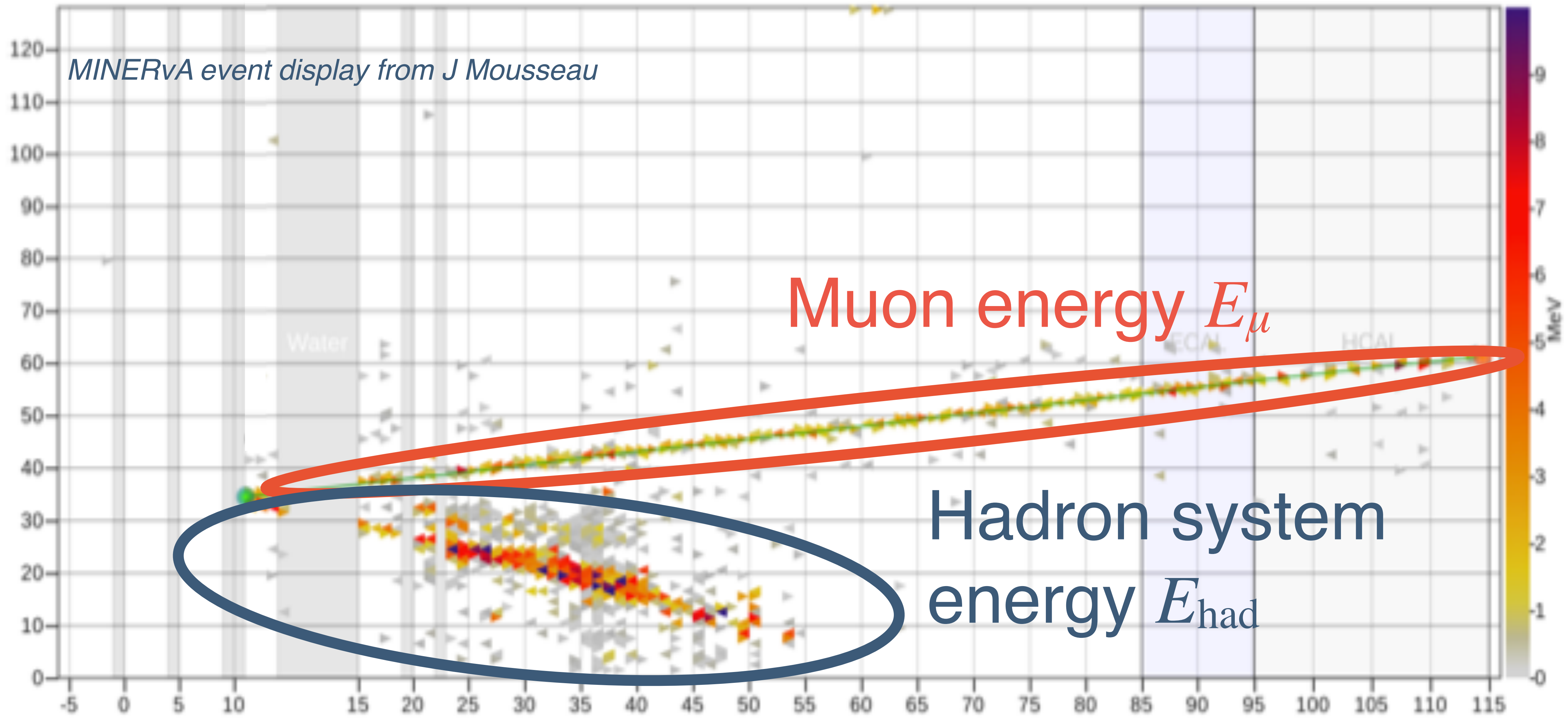

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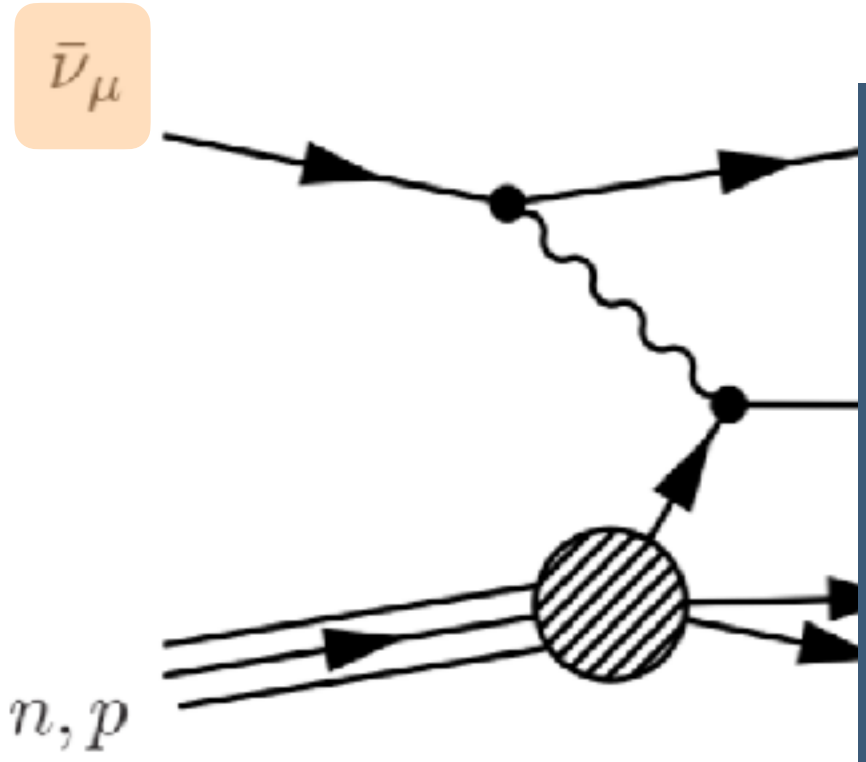
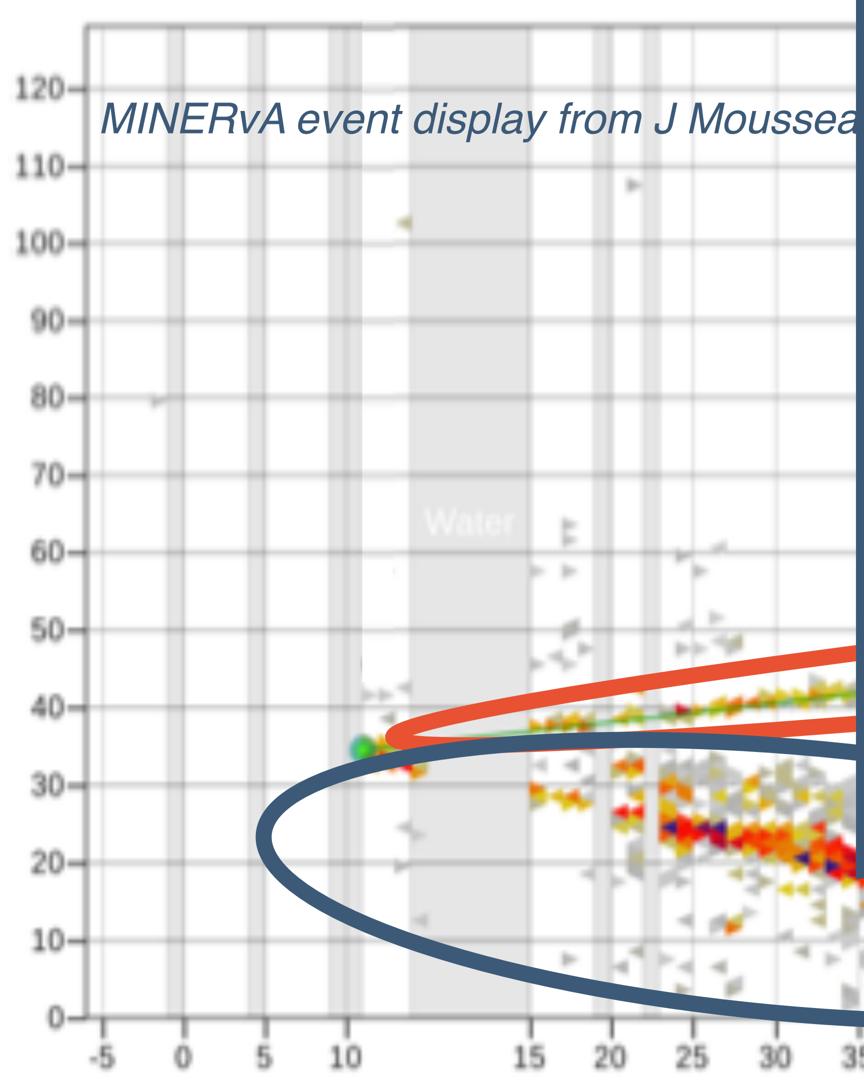
- For DIS, $0 < x < 1$
- Valence quarks have bigger x than sea quarks
- What are W and x for a CCQE interaction (whole nucleon knocked out)?

For CCQE: $x = 1$, $W = m_N$. This can be a good way of identifying a CCQE interaction!

Studying DIS interactions

Rather than trying to resolve individual particles, sum the **energy of the hadron system**





energy E_{had}

Other useful variables

Invariant mass W of final-state hadronic system

$^2 + 2m_N E_{\text{had}}$

e x is the fraction of he struck quark

Q^2

E_{had}

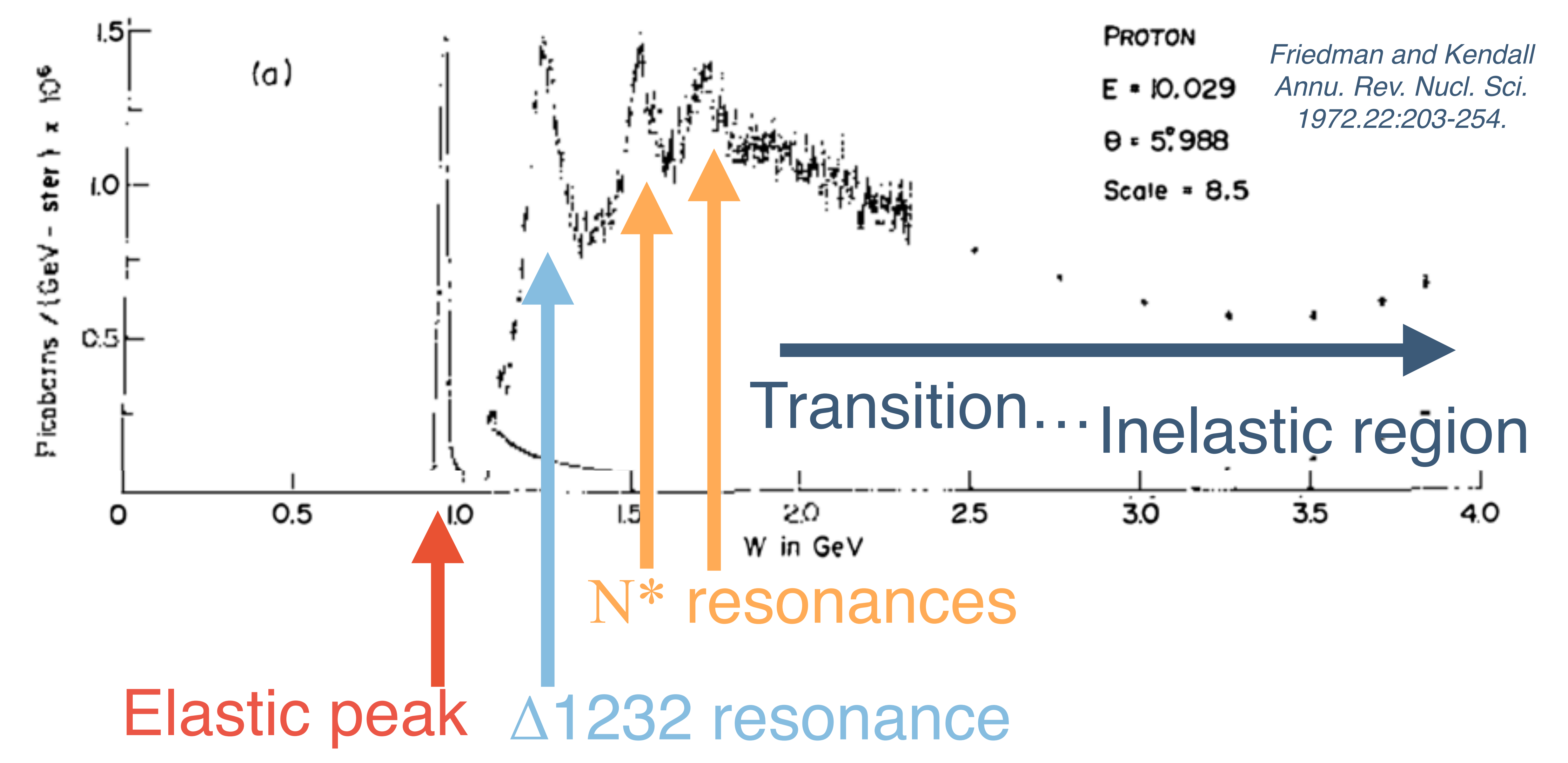
igger x than sea quarks

CCQE interaction

d out)?

For CCQE: $x = 1$, $W = m_N$. This can be a good way of identifying a CCQE interaction!

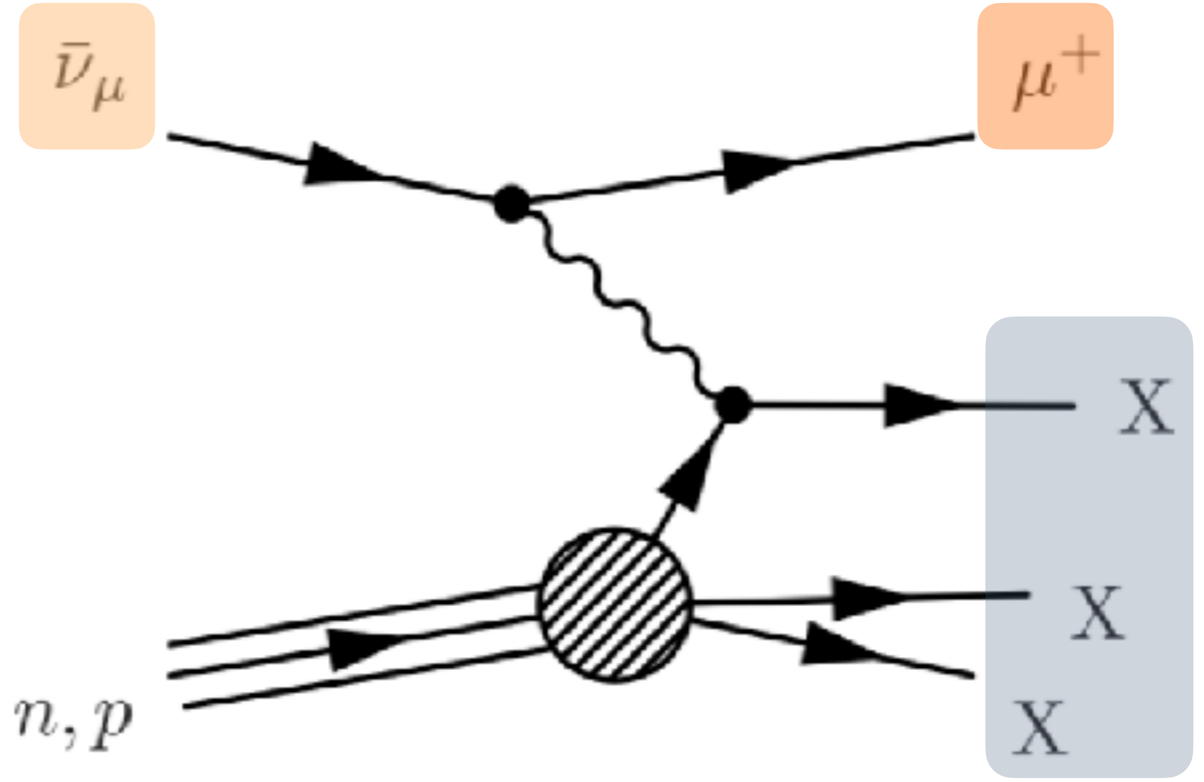
W distribution from an electron-scattering experiment



Friedman and Kendall Annu. Rev. Nucl. Sci. 1972.22:203-254.

Studying DIS interactions

Rather than trying to resolve individual particles, sum the **energy of the hadron system**



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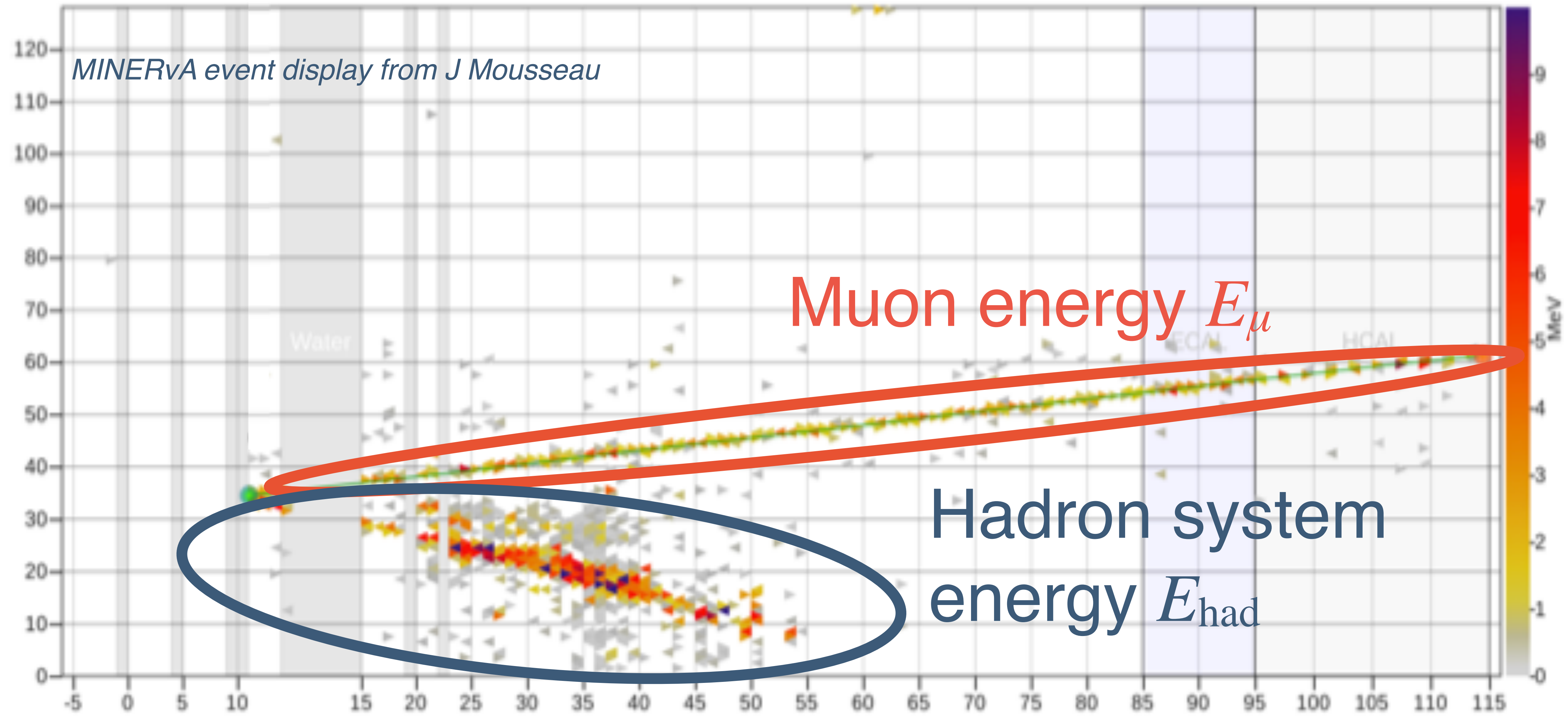


Muon energy E_μ

Hadron system energy $E_{\rm had}$

Other useful variables

Invariant mass W of final-state hadronic system

$$W^2 = m_N^2 - Q^2 + 2m_N E_{\rm had}$$

Bjorken scaling variable x is the fraction of momentum carried by the struck quark

$$x = \frac{Q^2}{2m_N E_{\rm had}}$$

Inelasticity y is the fraction of neutrino energy transferred to the hadronic system

$$y = \frac{E_{\rm had}}{E_\nu}$$

DIS cross sections

Not independent

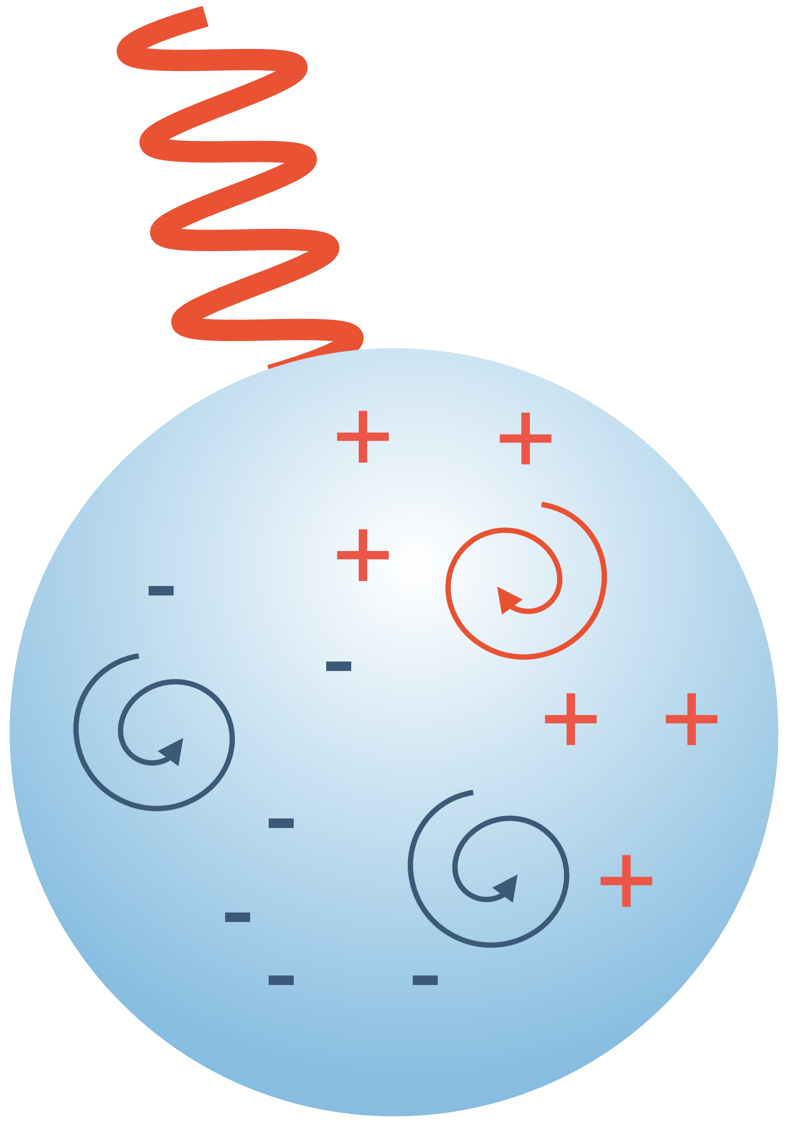
Only accessible through neutrino scattering

$$\frac{d^2\sigma(\nu h)}{dxdy} = \frac{G_{FS}^2}{2\pi}\left[xy^2 F_1^{\nu h}(x,y) + (1-y)F_2^{\nu h}(x,y) + y(1-\frac{y}{2})xF_3^{\nu h}(x,y)\right]$$

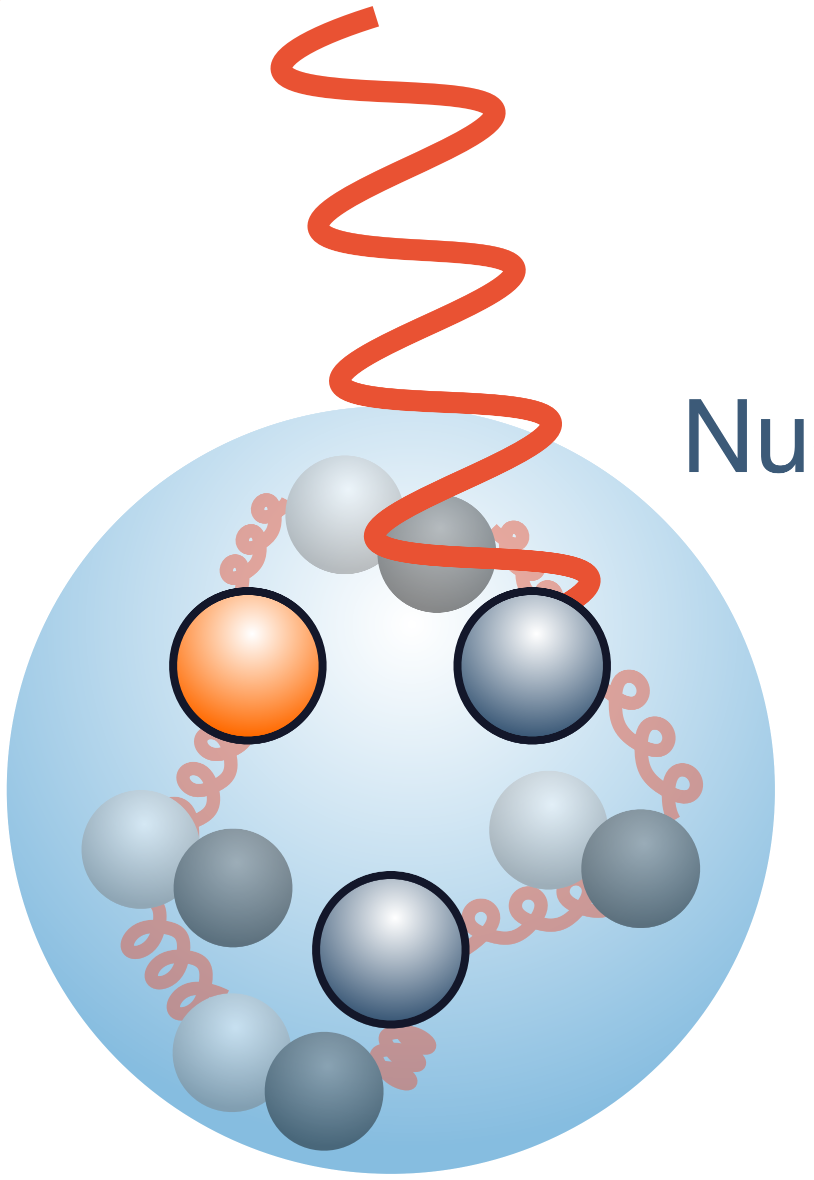
DIS cross sections depend on our new friends x (momentum fraction) and y (inelasticity)

Quasi-elastic scattering

Nucleon **form factors**: charge and current distribution as seen from **outside**



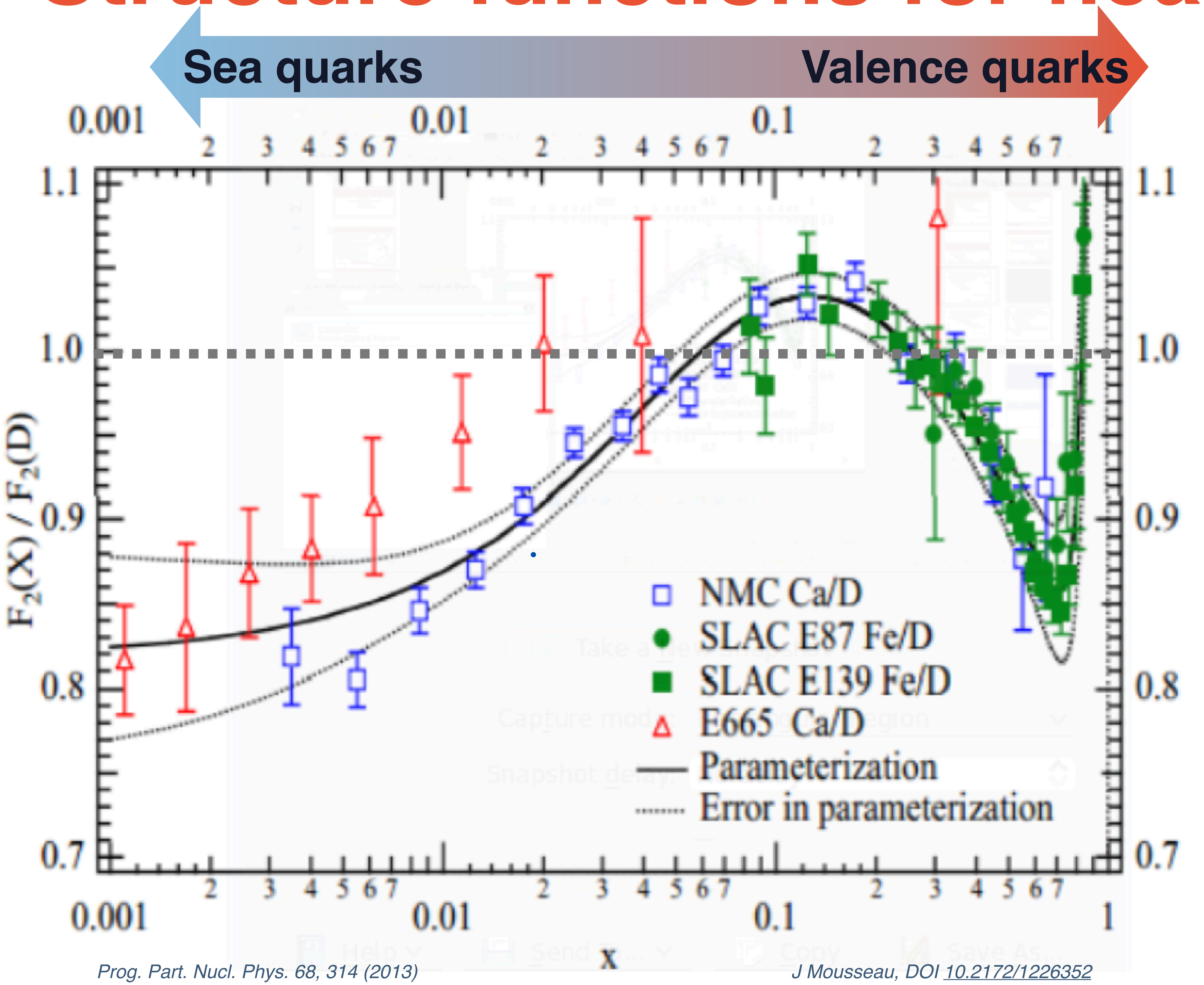
Deep inelastic scattering



Nucleon **structure functions**: describe momentum distribution of sea and valence quarks **inside** the nucleon

Neutrino scattering can help us understand structure functions - and they are **affected by the nucleus**

Structure functions for heavy nuclei



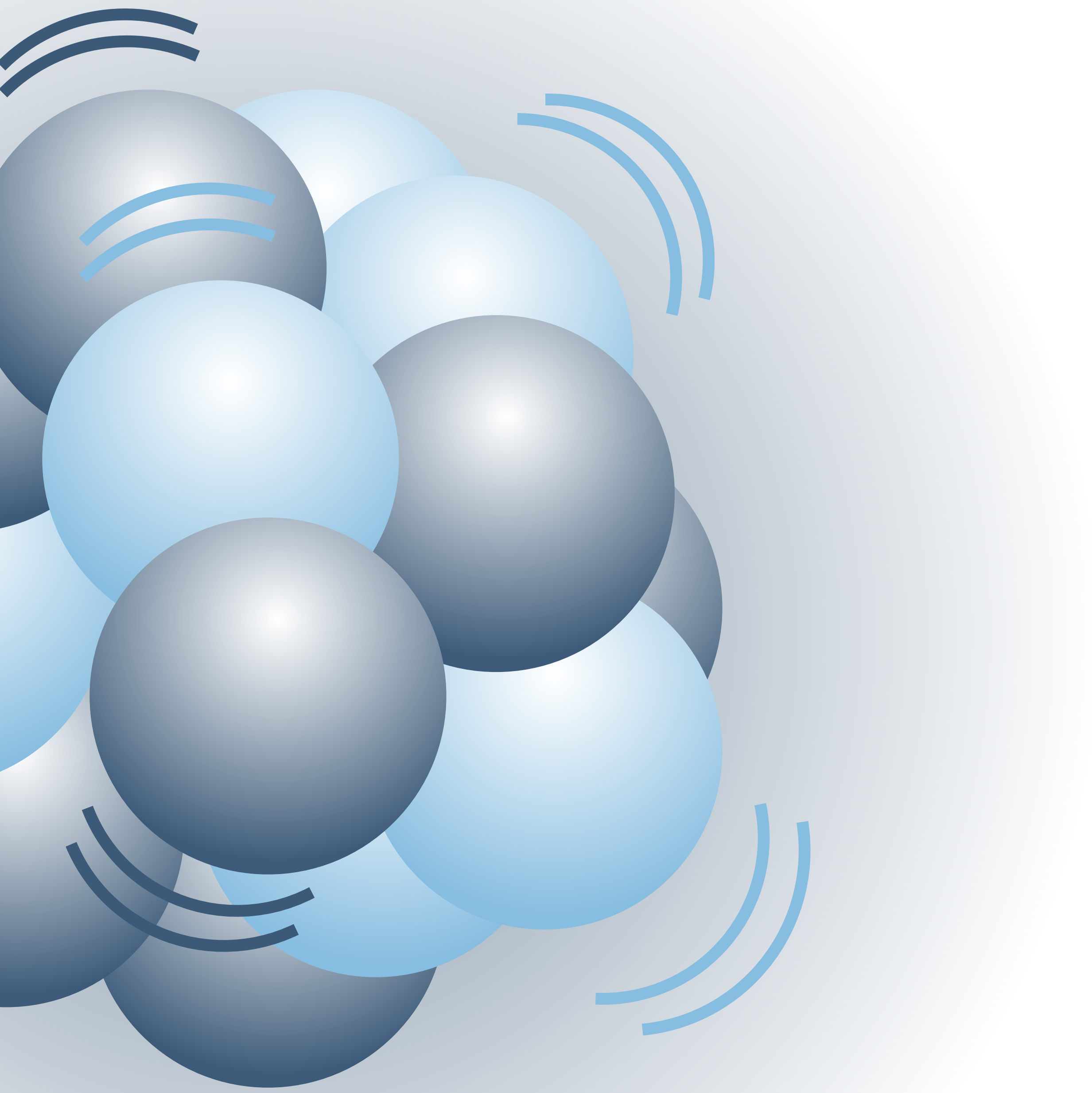
Prog. Part. Nucl. Phys. 68, 314 (2013)

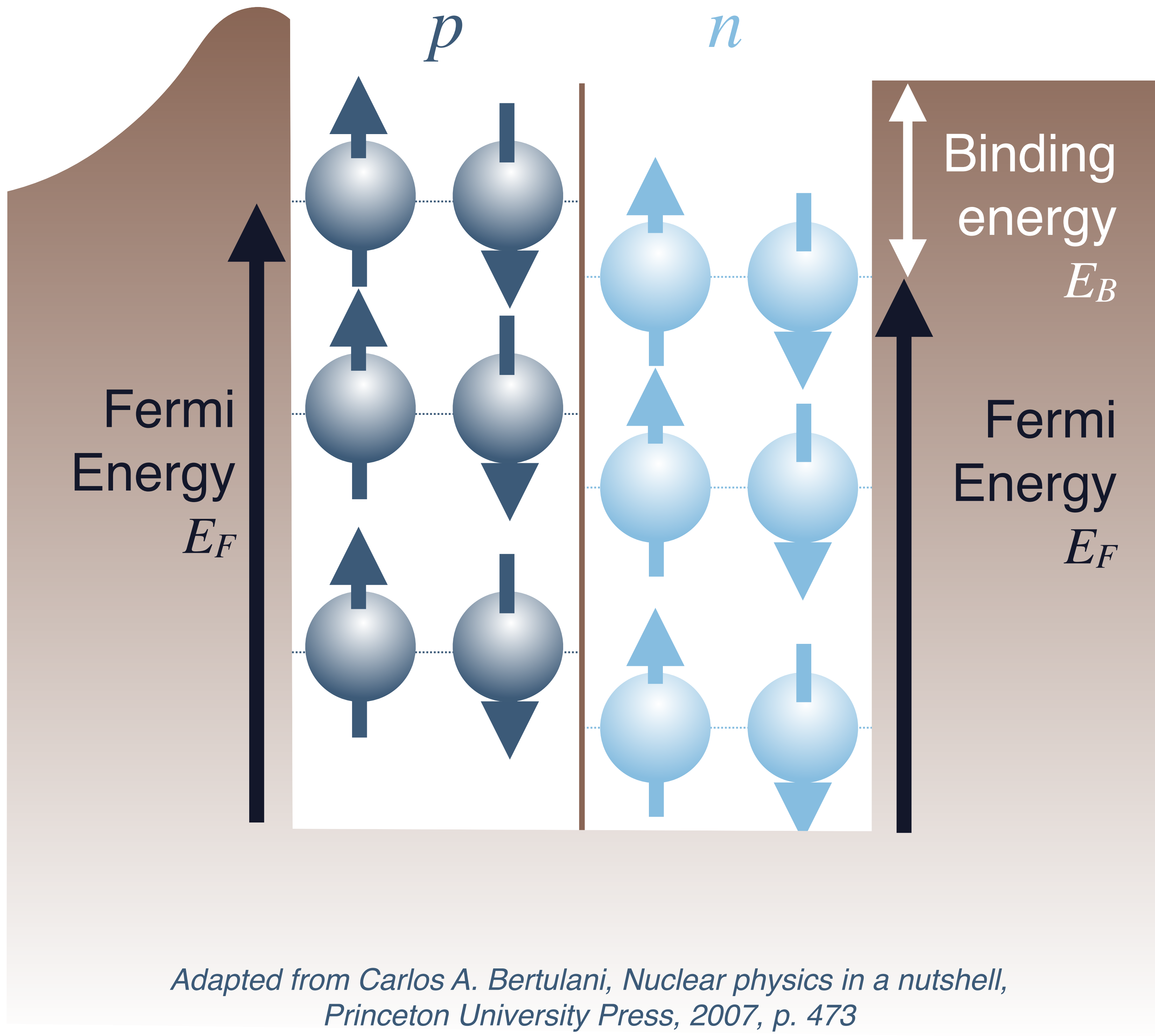
J Mousseau, DOI 10.2172/1226352

- Charged-lepton DIS from heavy nuclei (Ca, Fe) vs deuterium (^2H)
- x separates **sea** and **valance** quarks
- Nucleus has complicated effects on both…

Nuclear effects - Relativistic Fermi Gas models

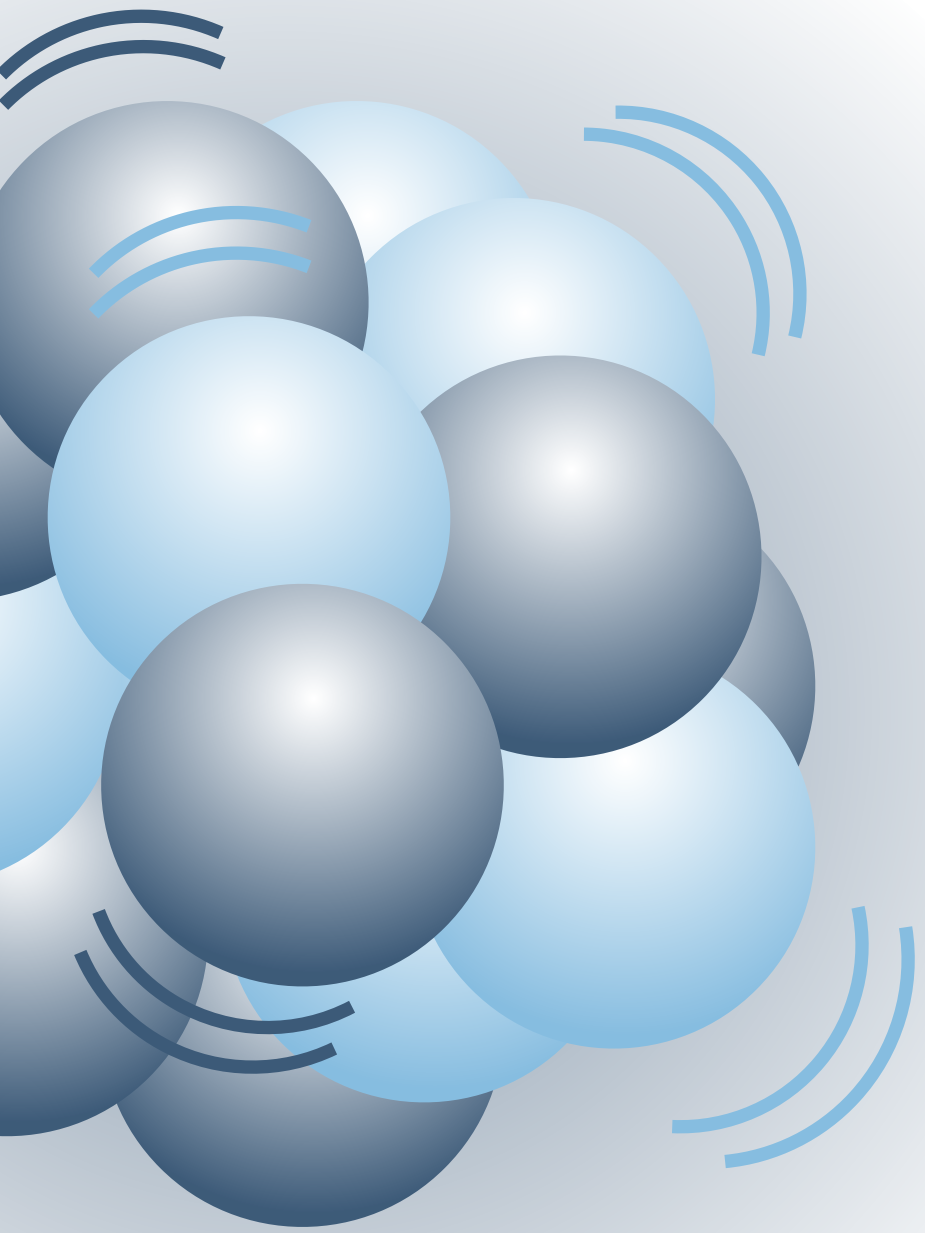
- Nucleons in a nucleus are not stationary: the nucleus affects them
- As fermions, they obey Fermi-Dirac statistics and Pauli exclusion principle: no identical particles in the same quantum state





Adapted from Carlos A. Bertulani, Nuclear physics in a nutshell, Princeton University Press, 2007, p. 473

Nuclear effects - Relativistic Fermi Gas models



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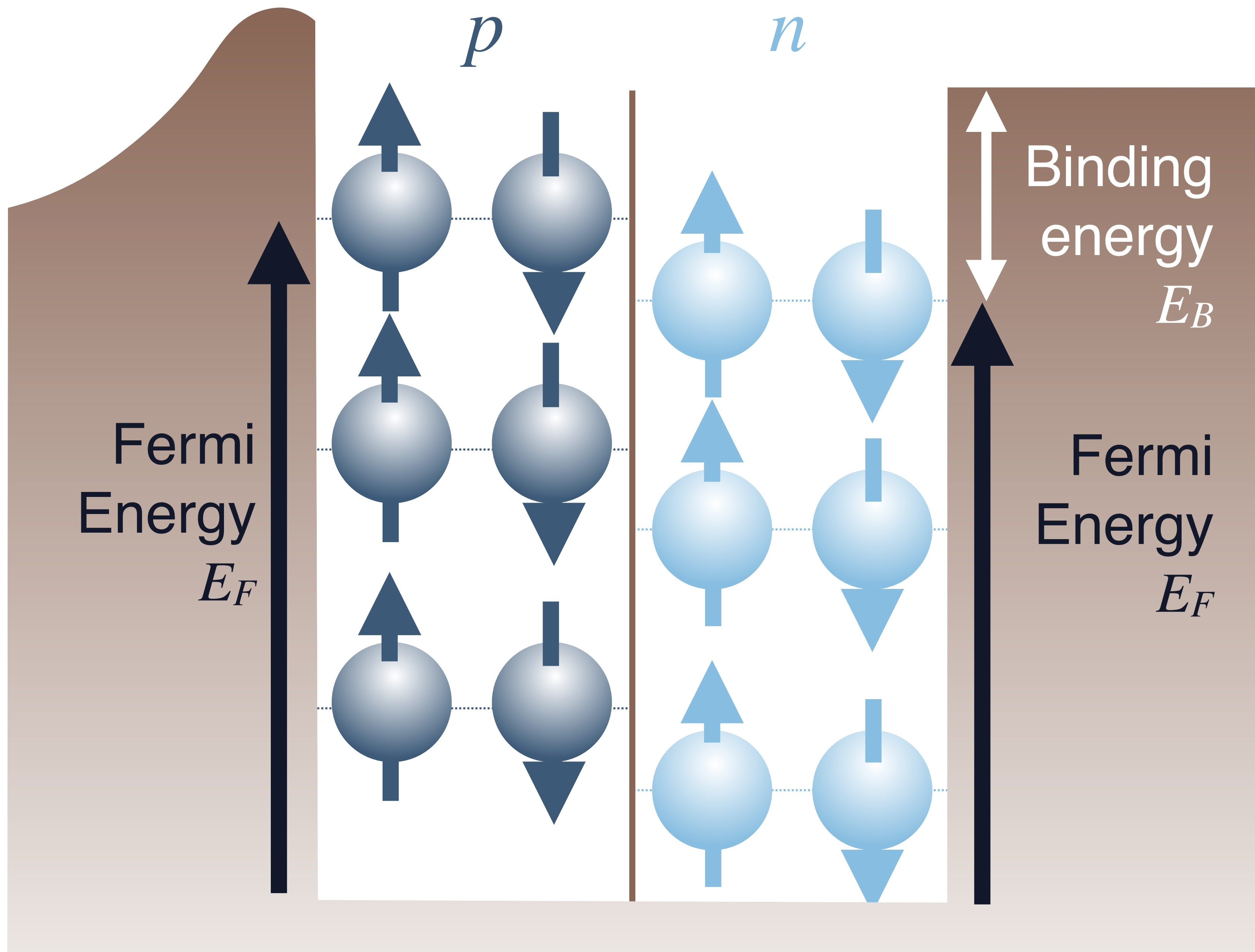
Global Fermi Gas Model

- Treat target nucleon as an independent particle (**impulse approximation**)
- With a **momentum** between 0 and E_F
  (argon: $E_F =$ 242 MeV (protons); 259 MeV (neutrons))
- **Pauli blocking** - momentum after interaction must be above Fermi momentum

R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972)



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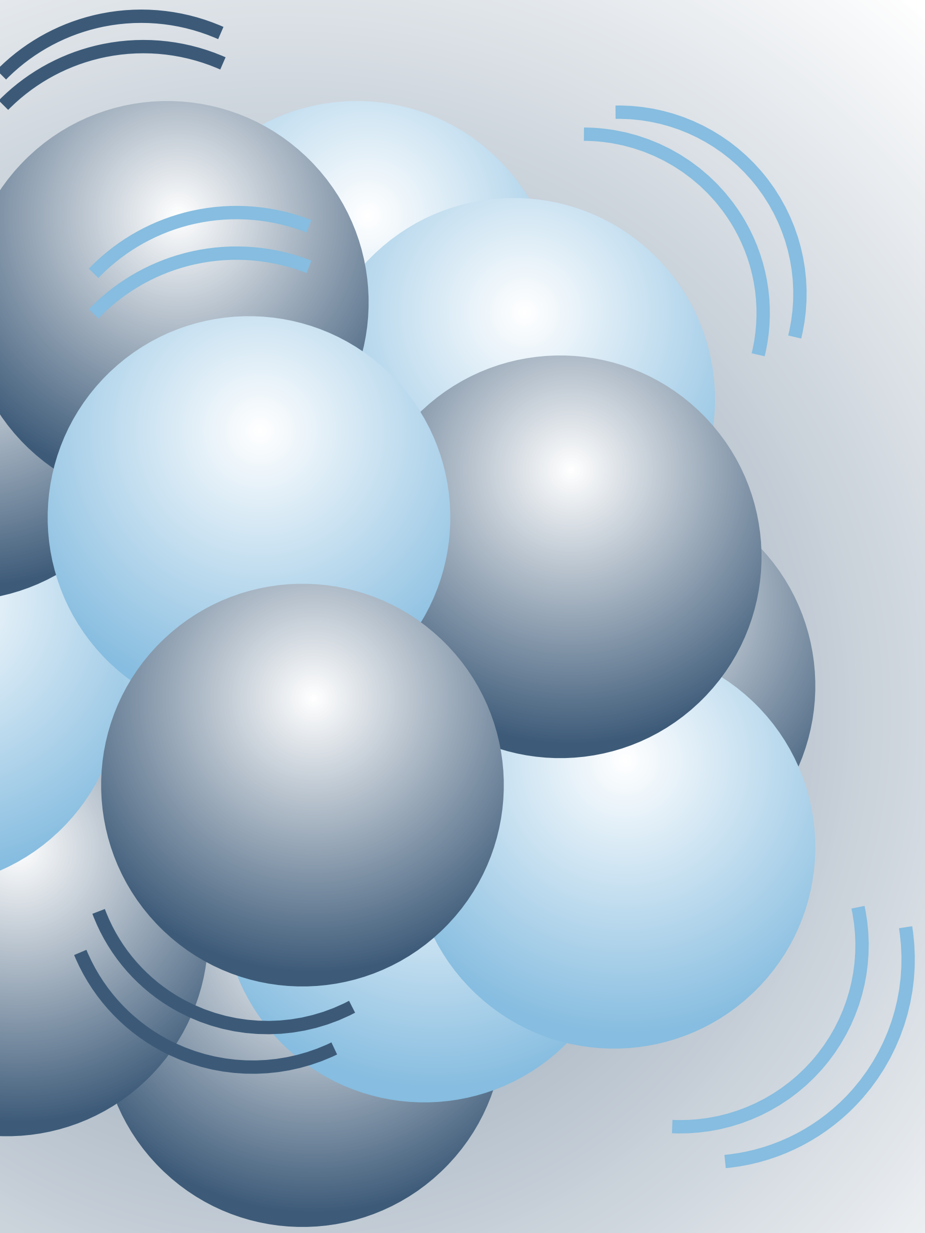

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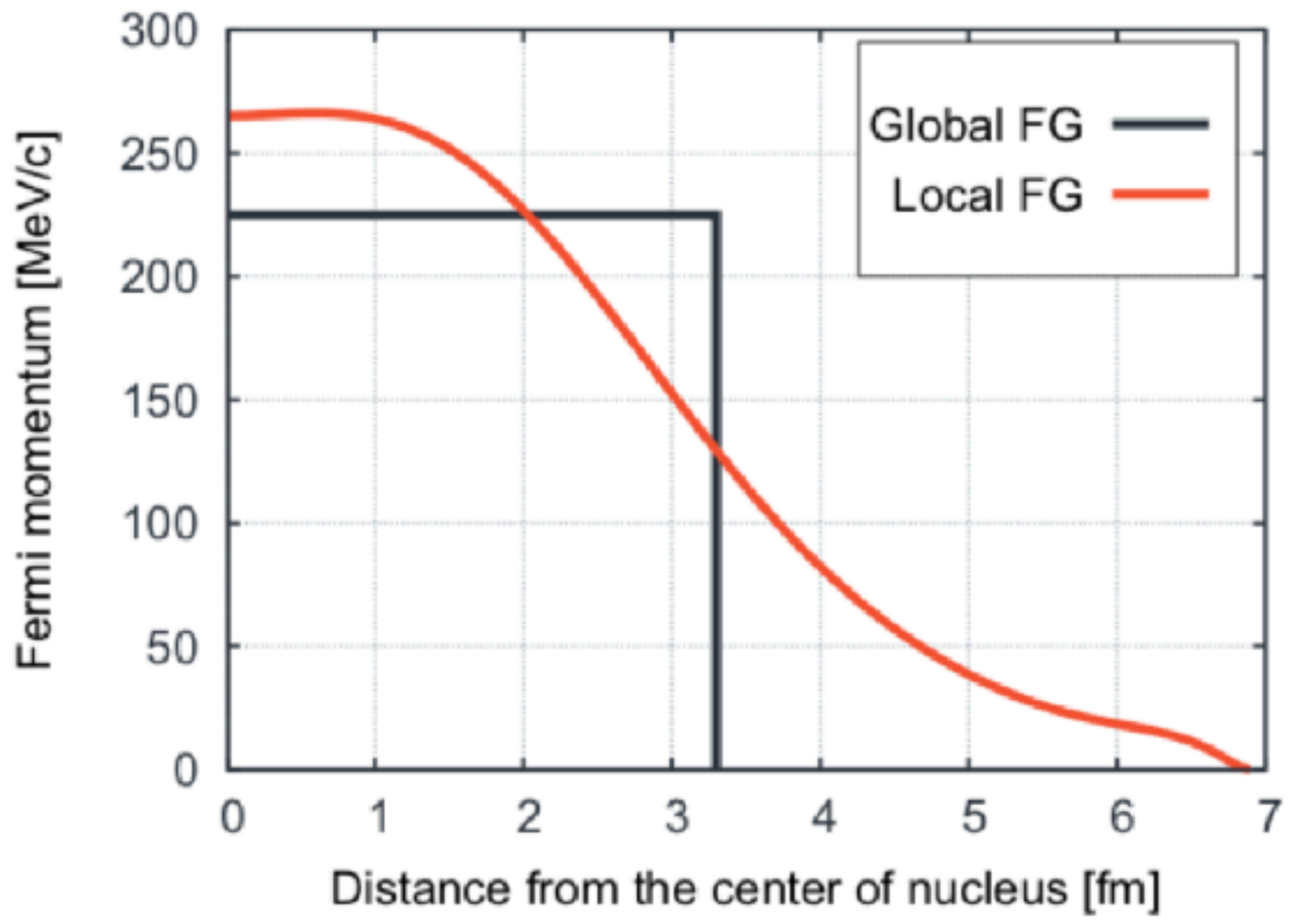
R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972)

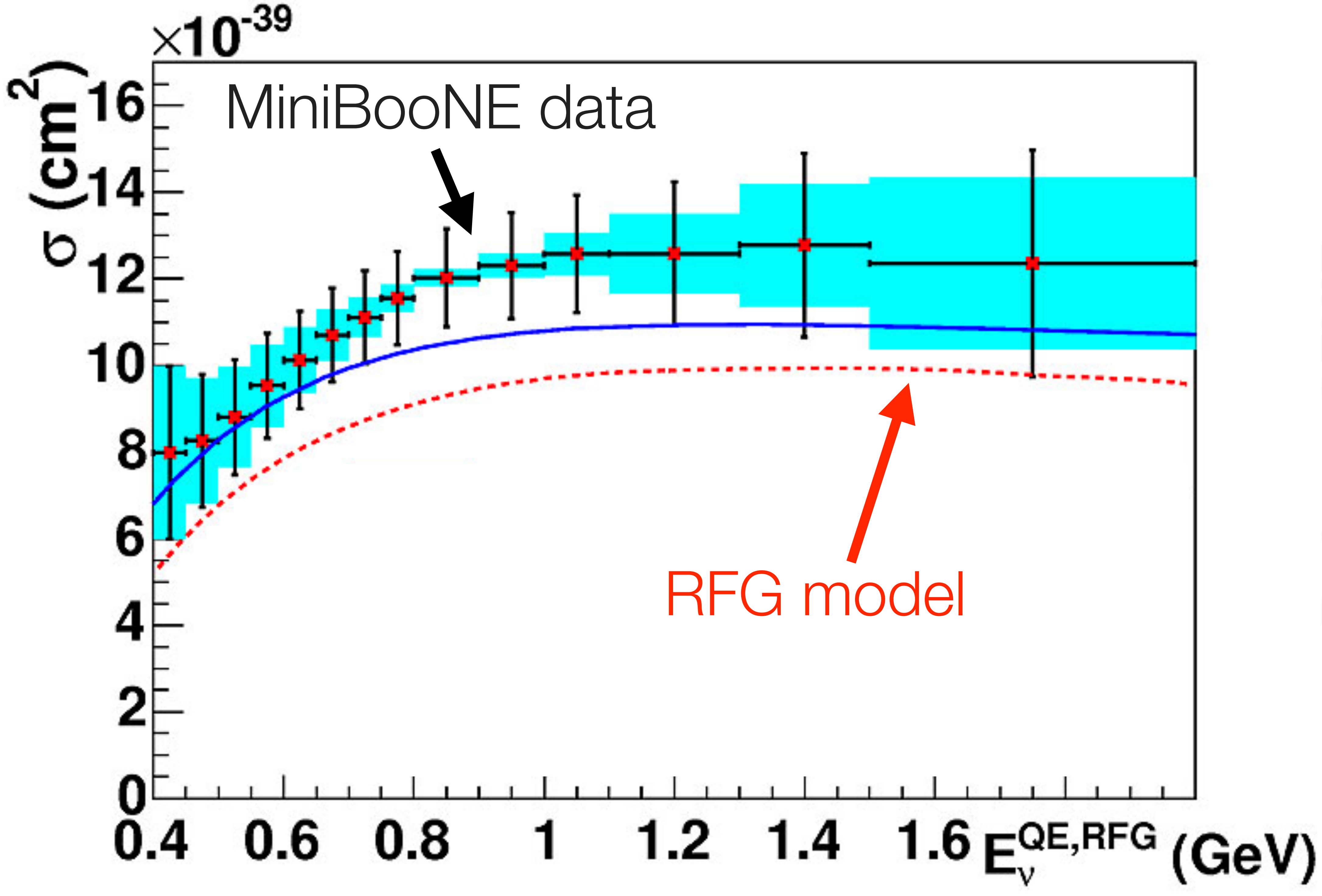
Local Fermi Gas Model

- Momentum distribution position-dependent
- Used in current versions of DUNE's simulation (GENIE)

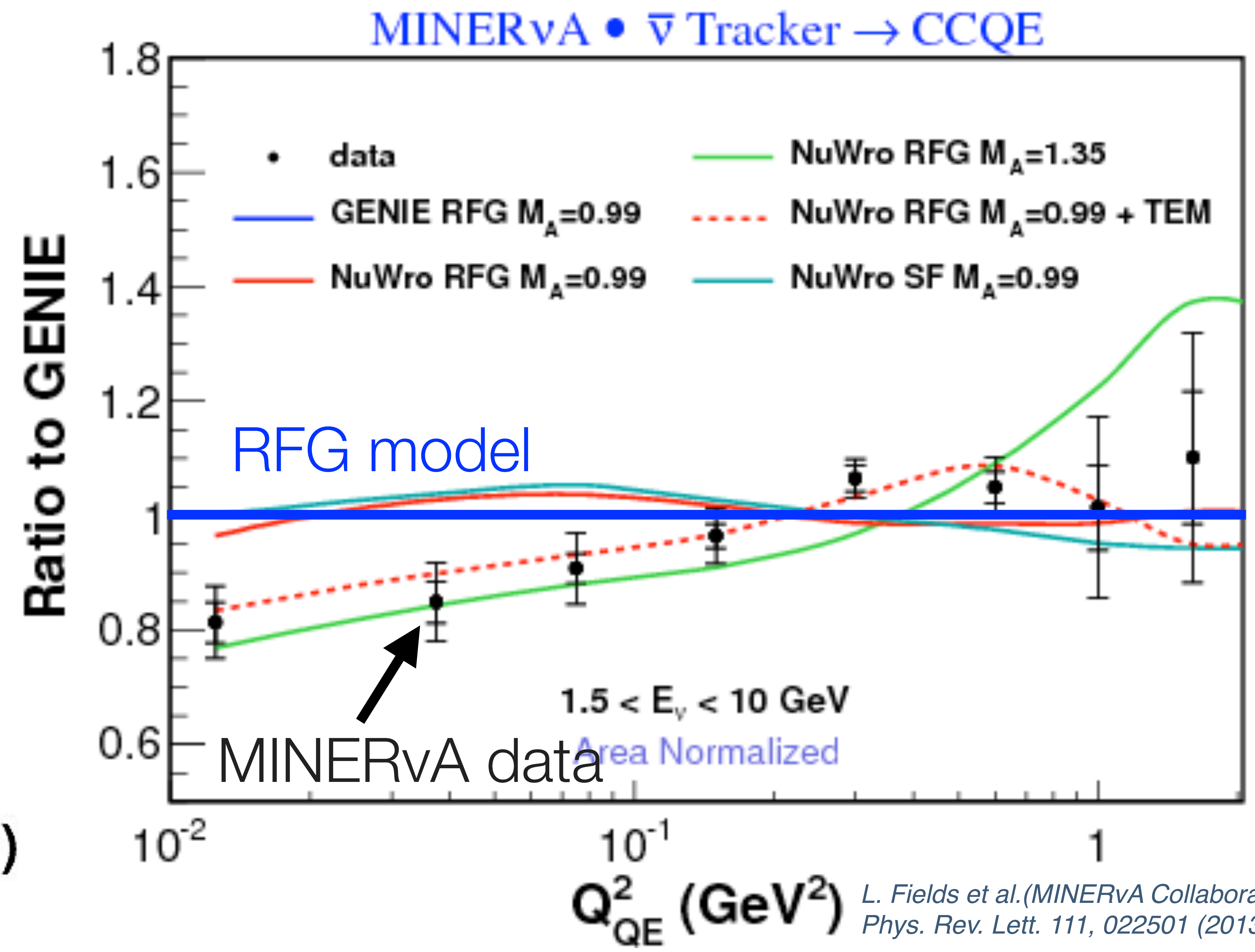


Tomasz Golan

But the Fermi Gas model isn’t enough to describe data



A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration)
Phys. Rev. D ***81****, 092005*



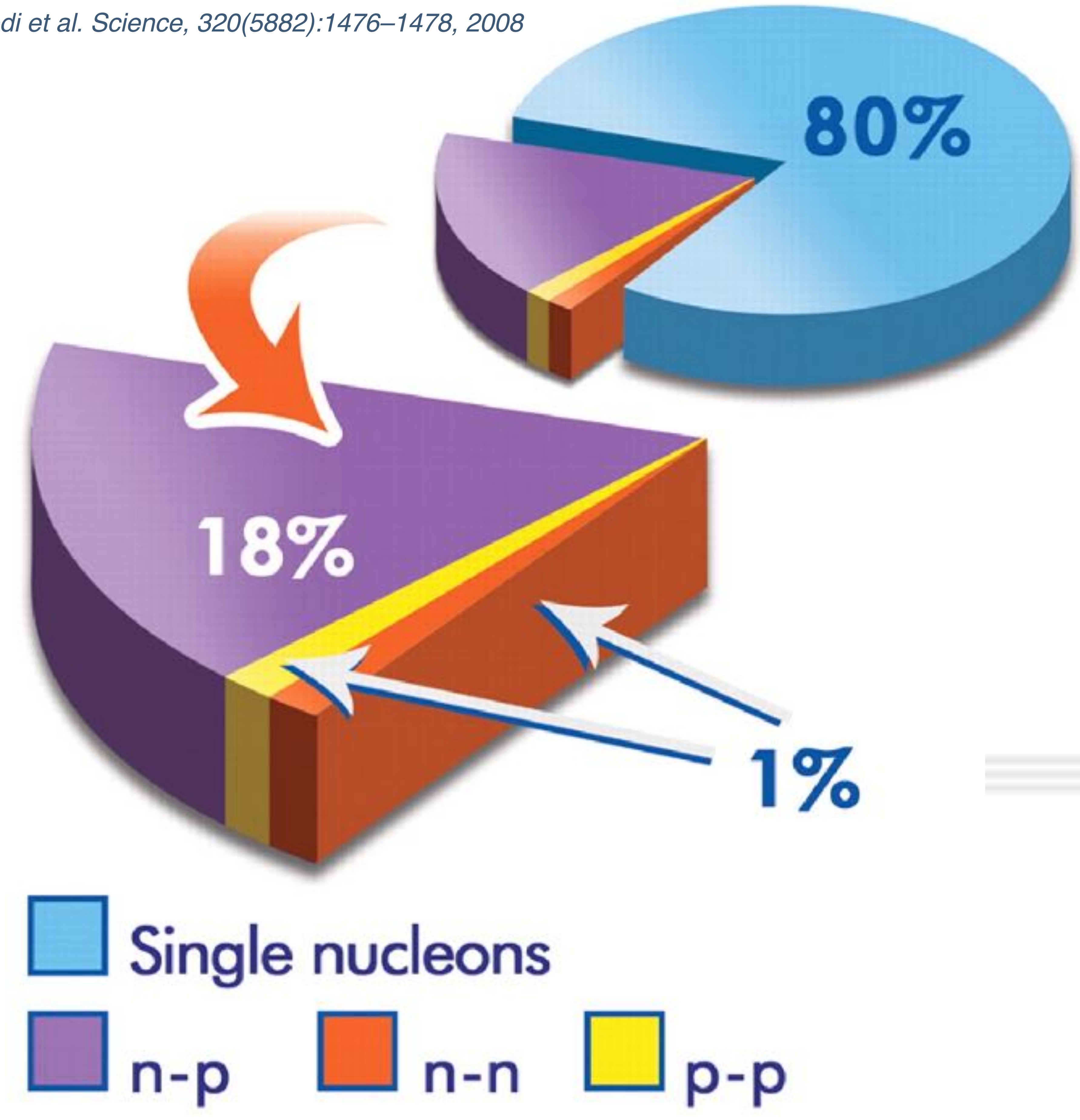
L. Fields et al.(MINERvA Collaboration)
Phys. Rev. Lett. 111, 022501 (2013)

Quasi-elastic neutrino and antineutrino cross sections measured at two experiments do not match the Fermi Gas model’s predictions:
what are we missing?

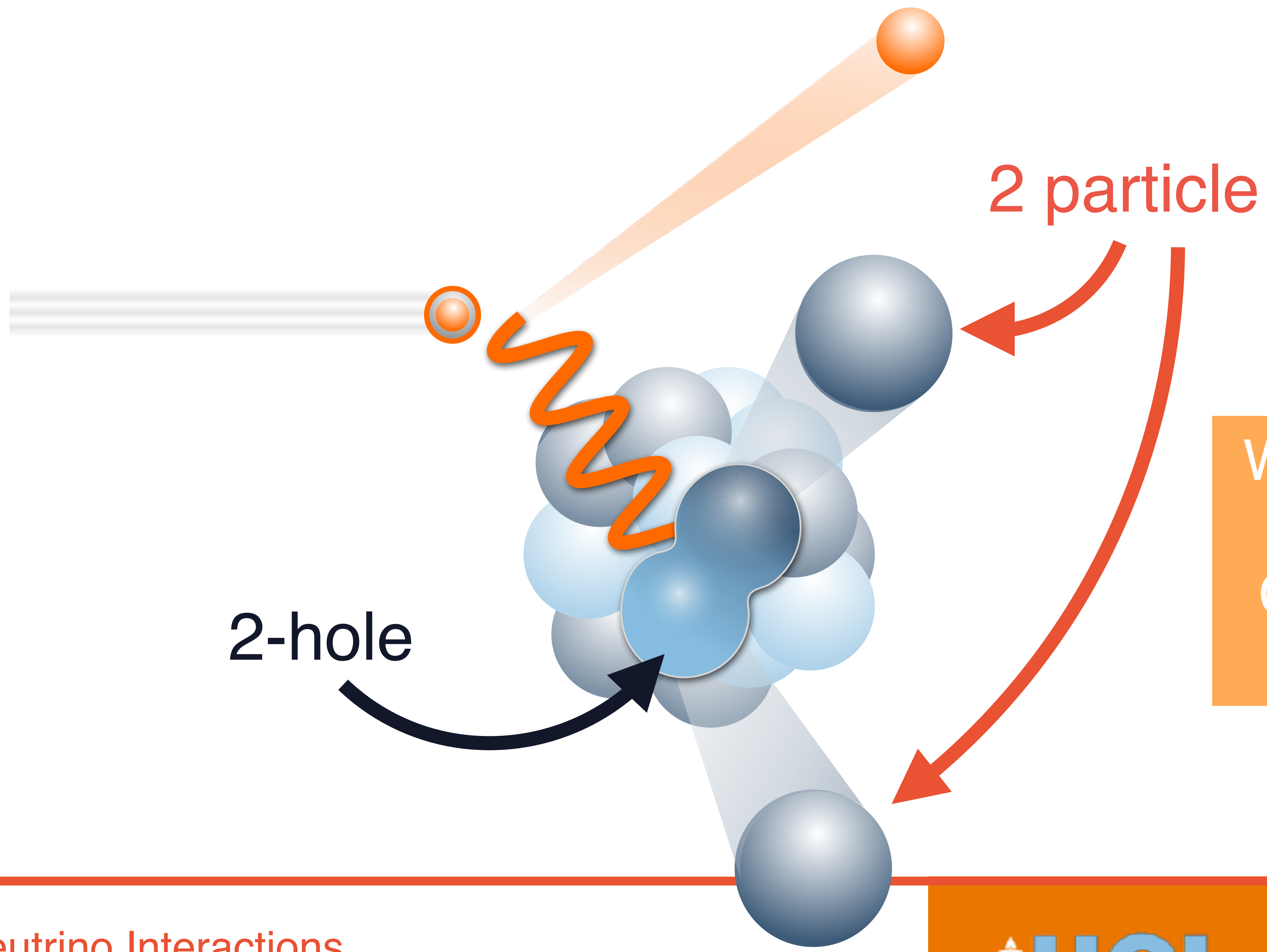
Multinucleon effects

Question 3

R. Subedi et al. Science, 320(5882):1476–1478, 2008

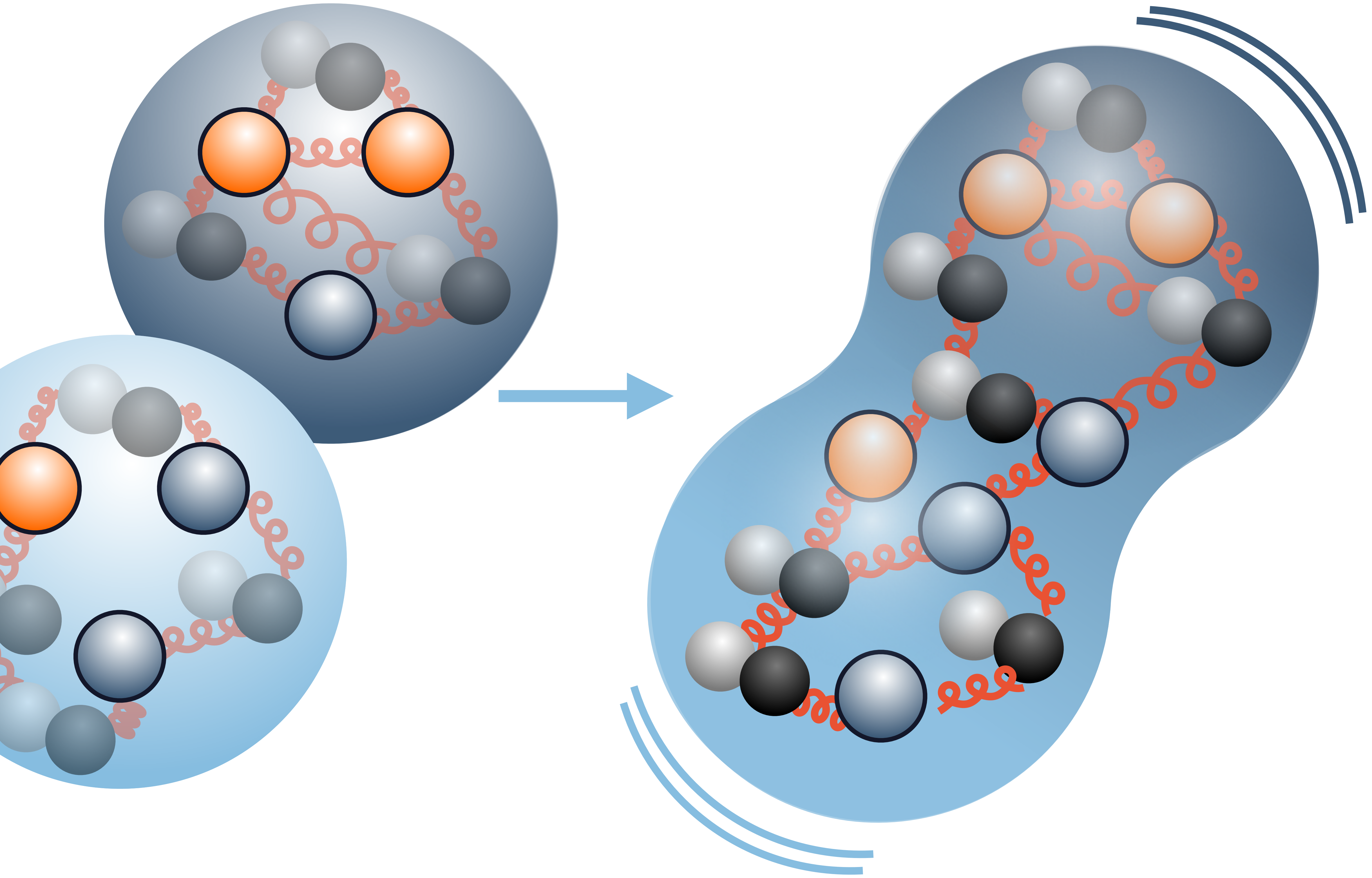


- RFG/LFG assume scattering from a single nucleon…
- …but 20% of nucleons in nuclei form correlated **pairs**
- Scattering from a pair can **knock out the partner** (2p2h: two particle, two hole)
- **Energy reconstruction** like the QE formula will be invalid
- Nuclear effects are **complicated** and **not fully understood**



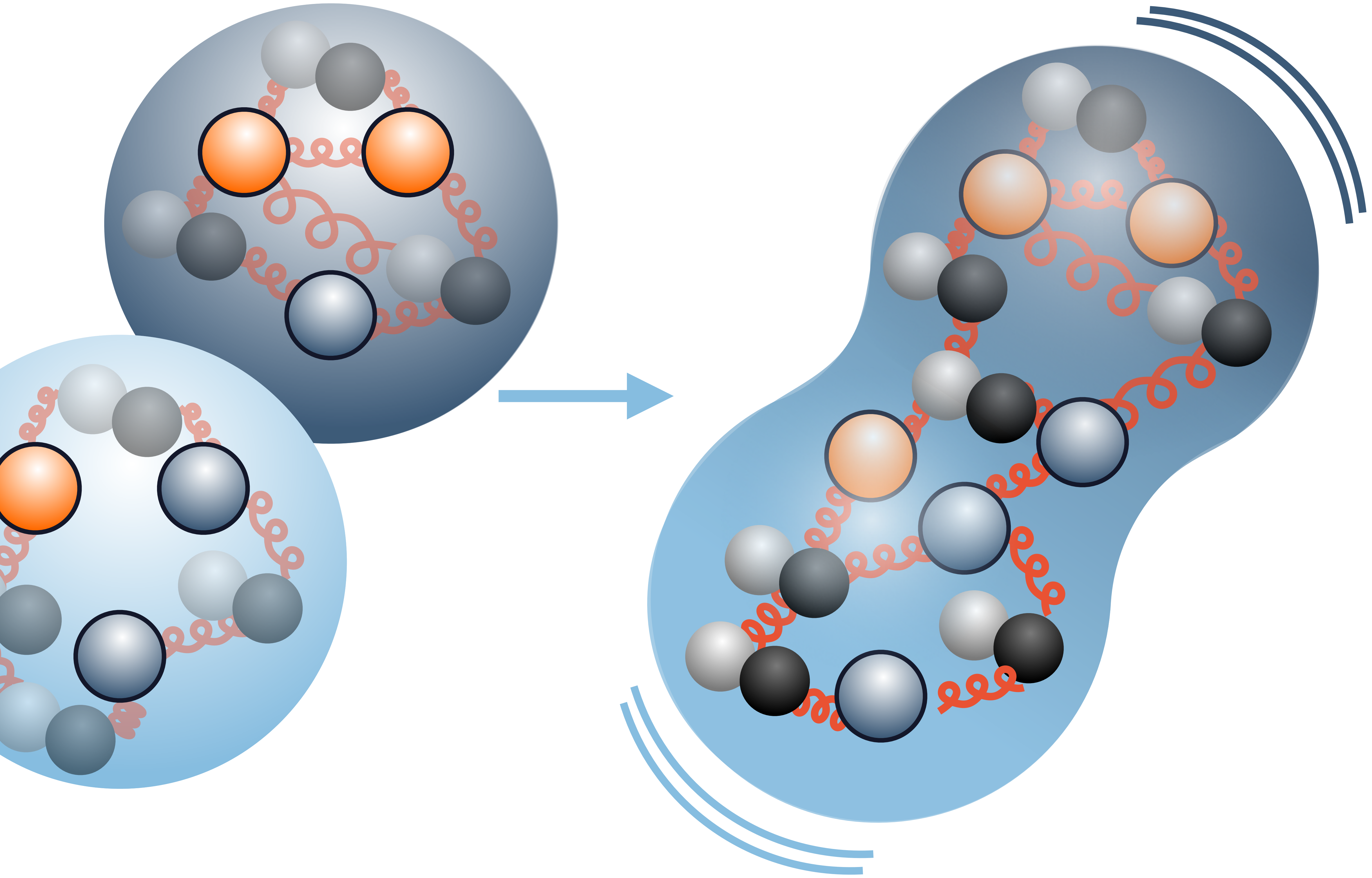
What final states would you expect to see for 2p2h CCQE scattering of ν_μ and $\bar{\nu}_\mu$?

Short-range correlations (SRC)



- Wave-functions overlap for a brief period
- Two nucleons with large, opposite momenta
  - **Individual** momenta > Fermi momentum k_F ($x > 1$)
  - **Center-of-mass** momentum of pair < k_F
- Almost all high-momentum nucleons are in SRC pairs

Short-range correlations (SRC)



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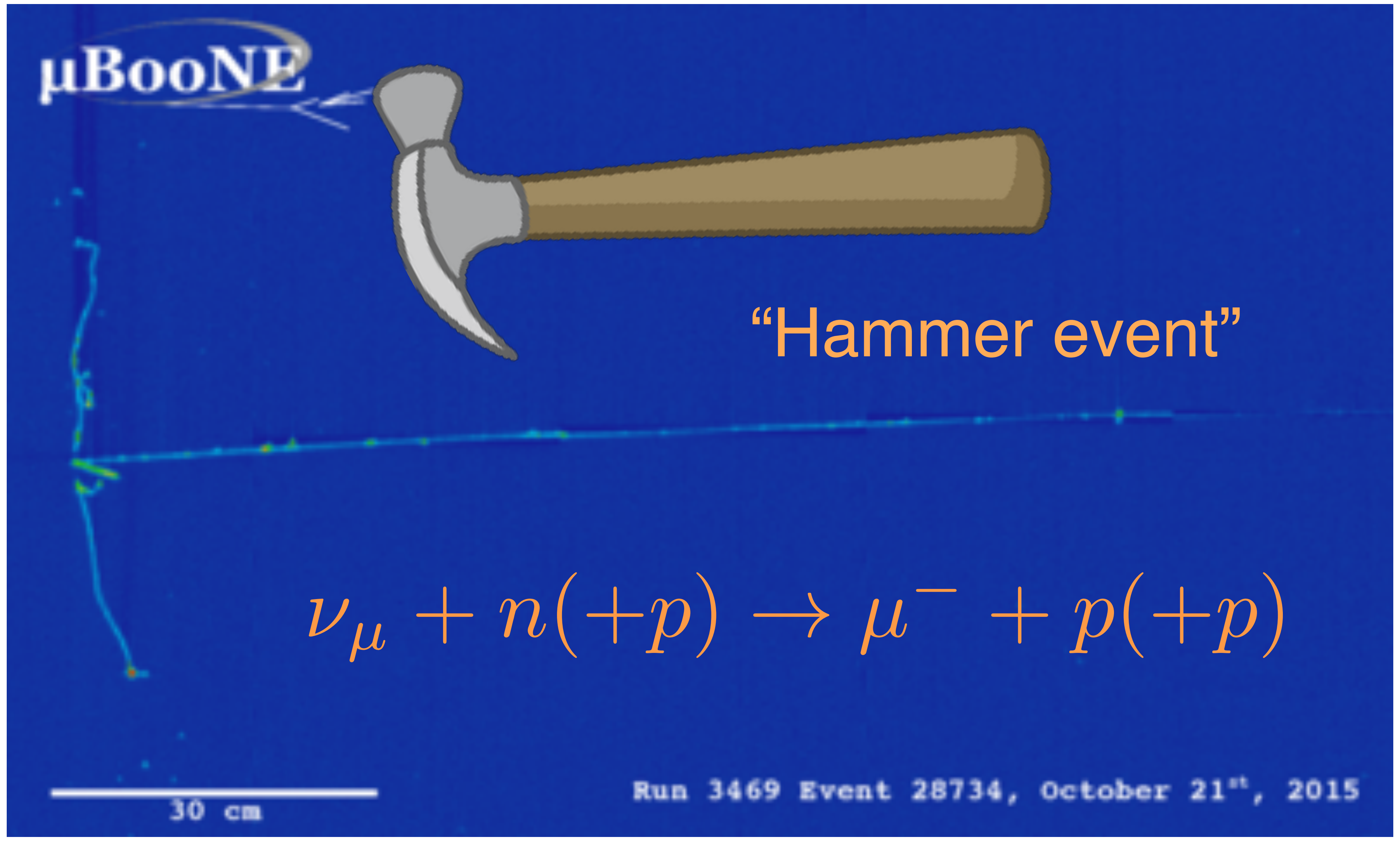
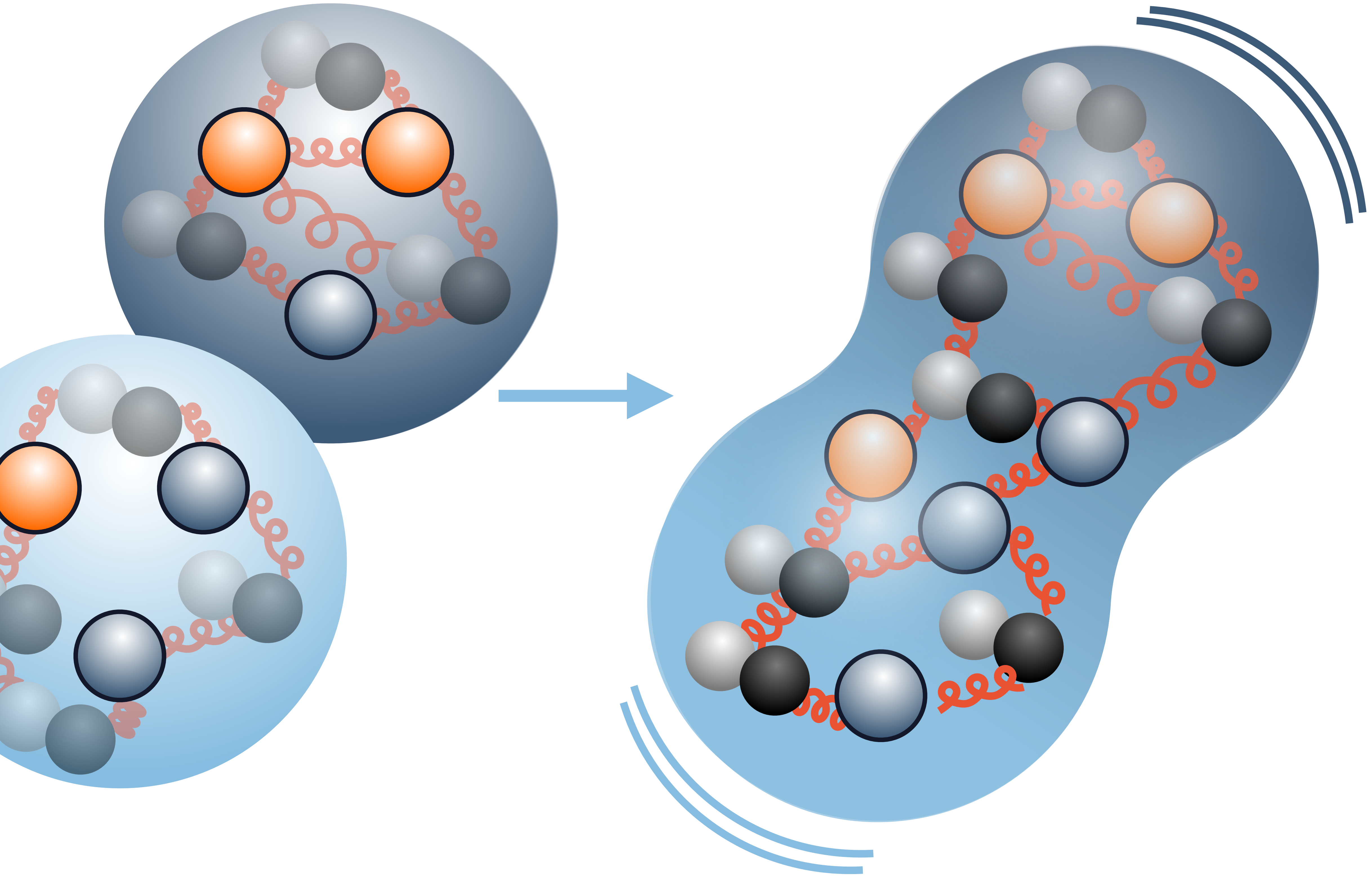
- Scattering signature is back-to-back protons



$$\nu_\mu + n(+p) \rightarrow \mu^- + p(+p)$$

Short-range correlations (SRC)



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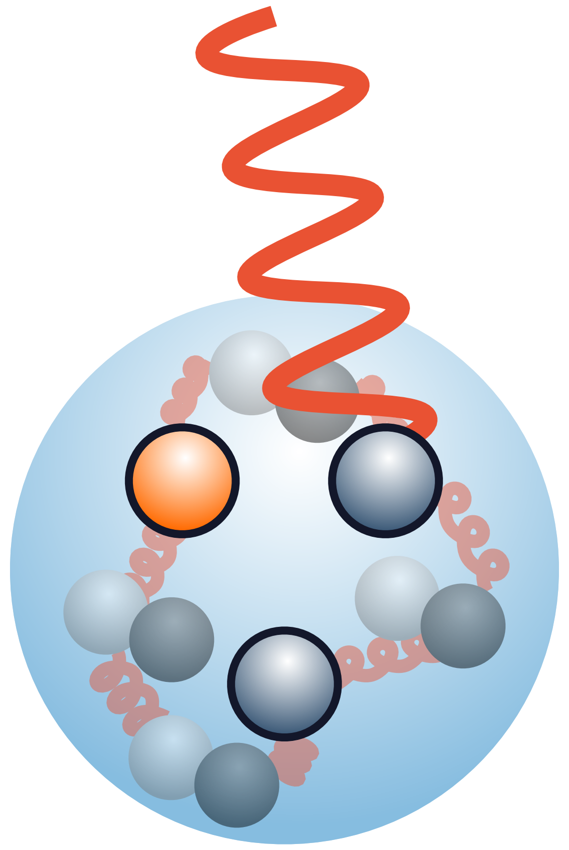
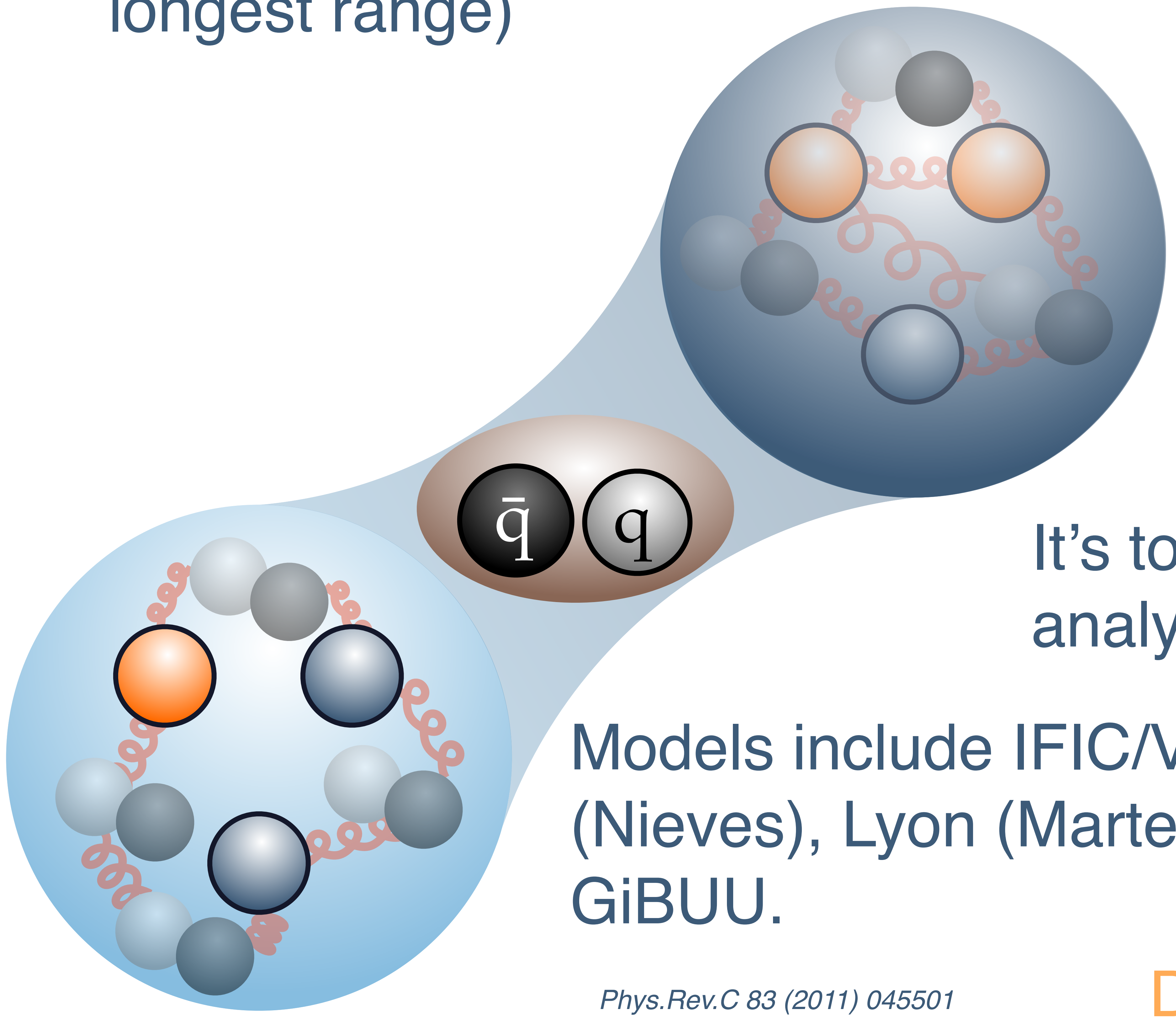
- Almost all high-momentum nucleons are in SRC pairs
- Scattering signature is back-to-back protons
- Being in an SRC pair also modifies the nucleon, affecting the structure function (quark distribution)



Remember - the structure functions affect deep inelastic scattering rates. Could this explain the EMC effect?

Meson-exchange currents (MEC)

Another way of considering the binding between a nucleon pair is exchange of virtual mesons (pions are the lightest, so have the longest range)



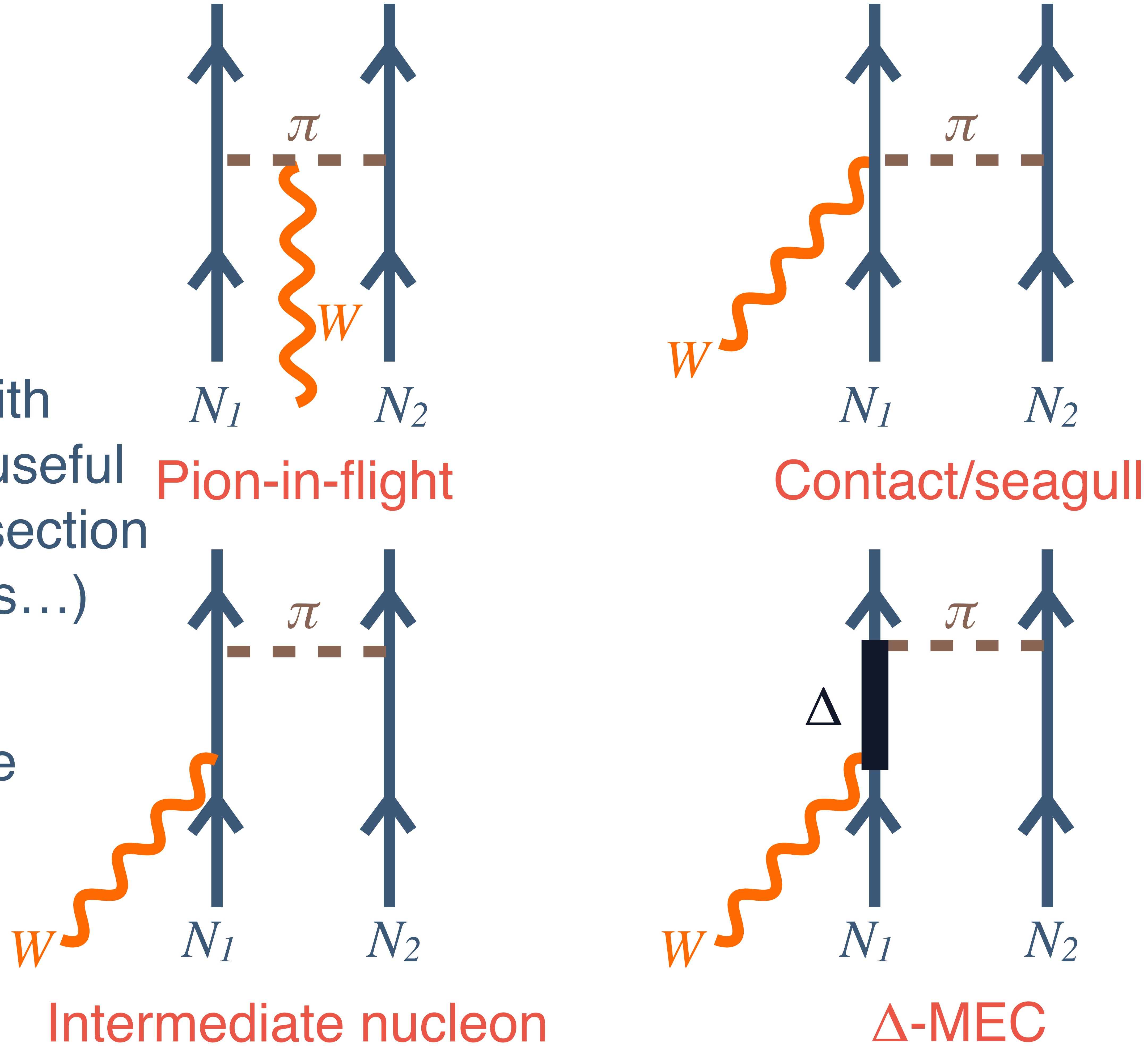
You can model this with Feynman diagrams (useful for calculating cross section kinematic distributions…)

It's too complicated to solve analytically!

Models include IFIC/Valencia (Nieves), Lyon (Marteau/Martini), and GiBUU.

Phys.Rev.C 83 (2011) 045501

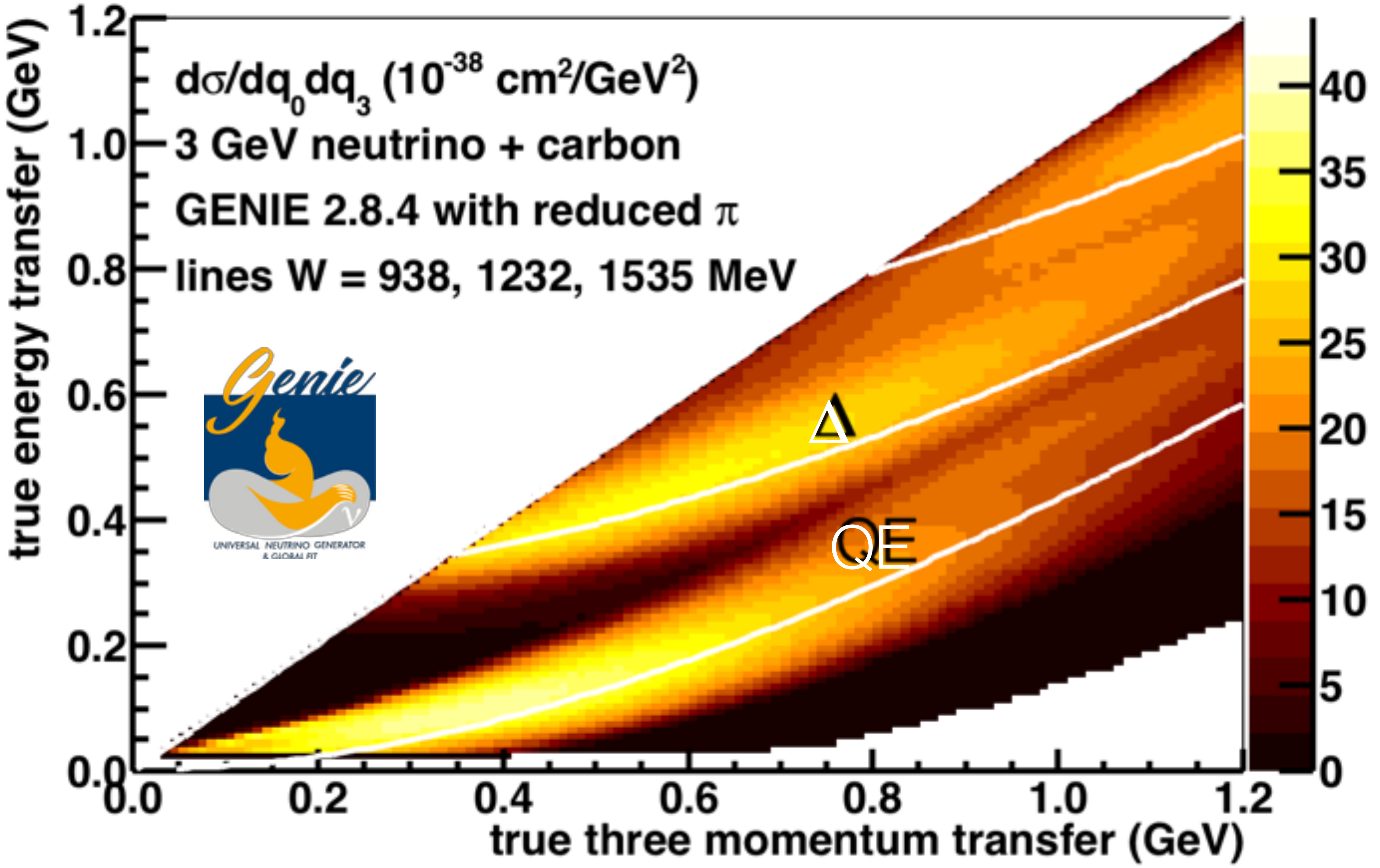
Adapted from Annals of Physics, 131(2):451 – 493, 1981



Different experiments use different models; none fully matches data yet

Studying nuclear effects with neutrino data

Simulated neutrino-carbon cross section without multi-nucleon effects



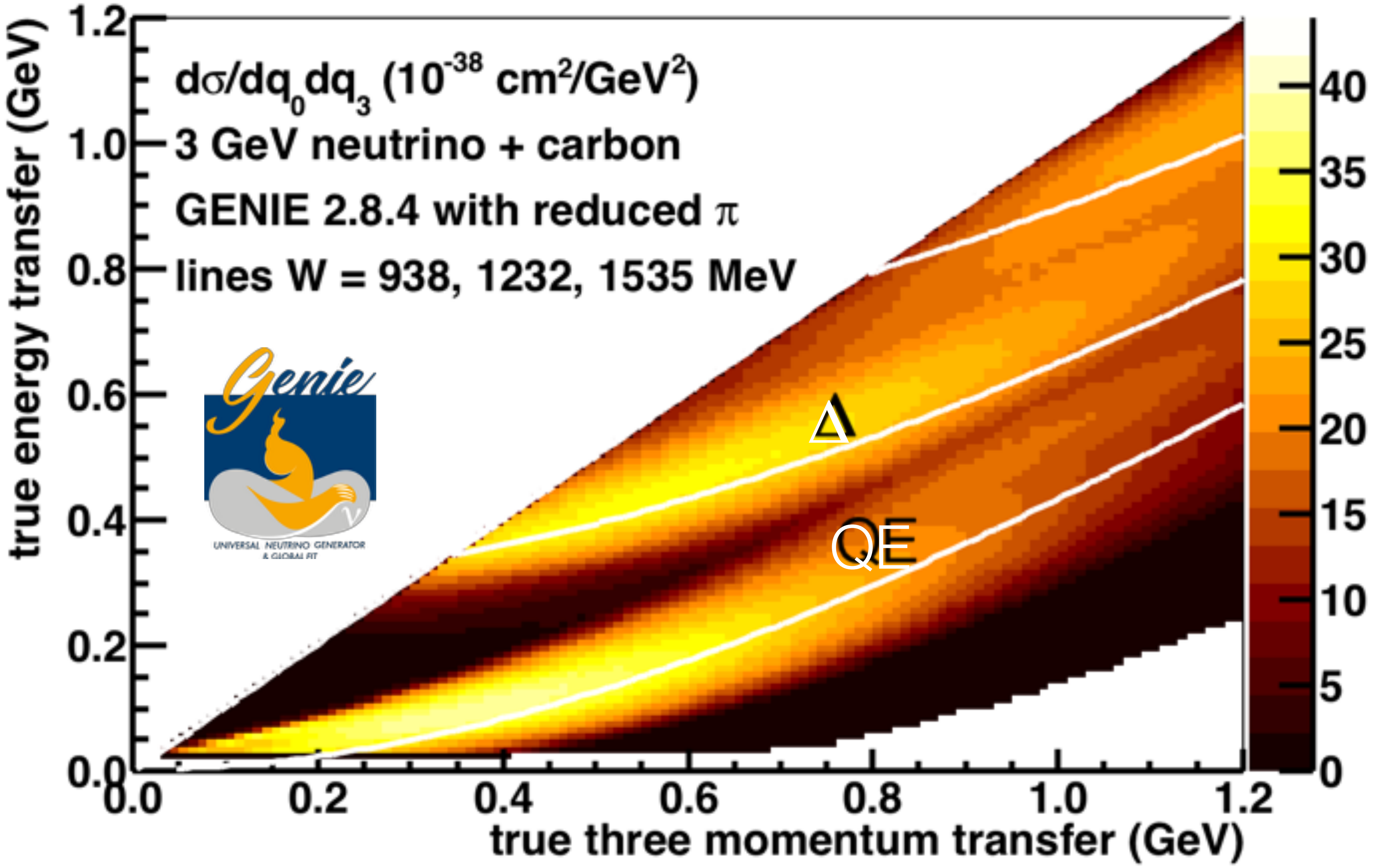
Choose variables that separate out interaction types → How would nuclear effects change this? →

Nucl.Instrum.Meth.A614 (2010) 87-104

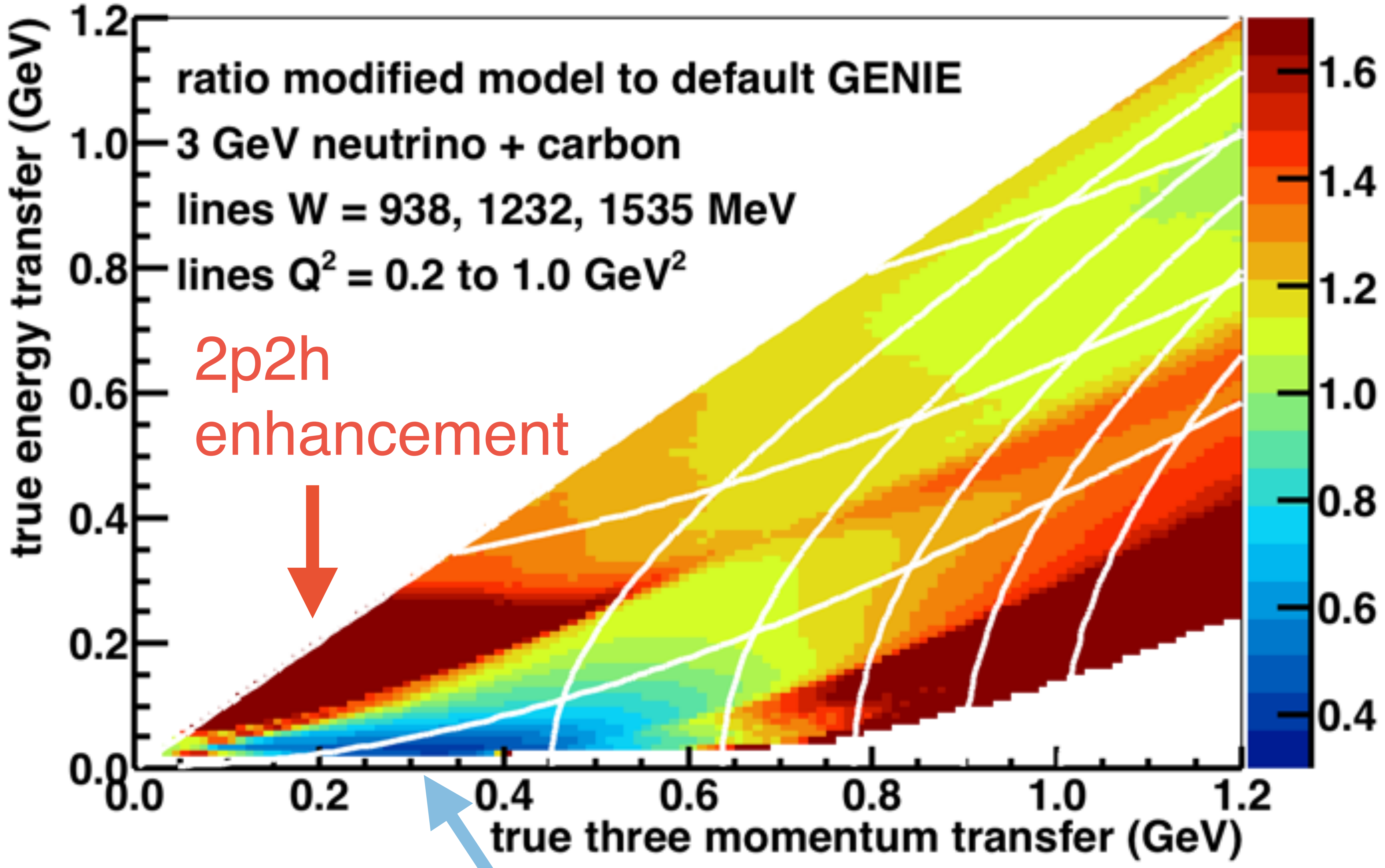
P. Rodrigues, Fermilab wine and cheese 11 Dec 2015

Studying nuclear effects with neutrino data

Simulated neutrino-carbon cross section without multi-nucleon effects



Add Valencia/Nieves multi-nucleon model



2p2h enhancement

Choose variables that separate out interaction types → How would nuclear effects change this? →

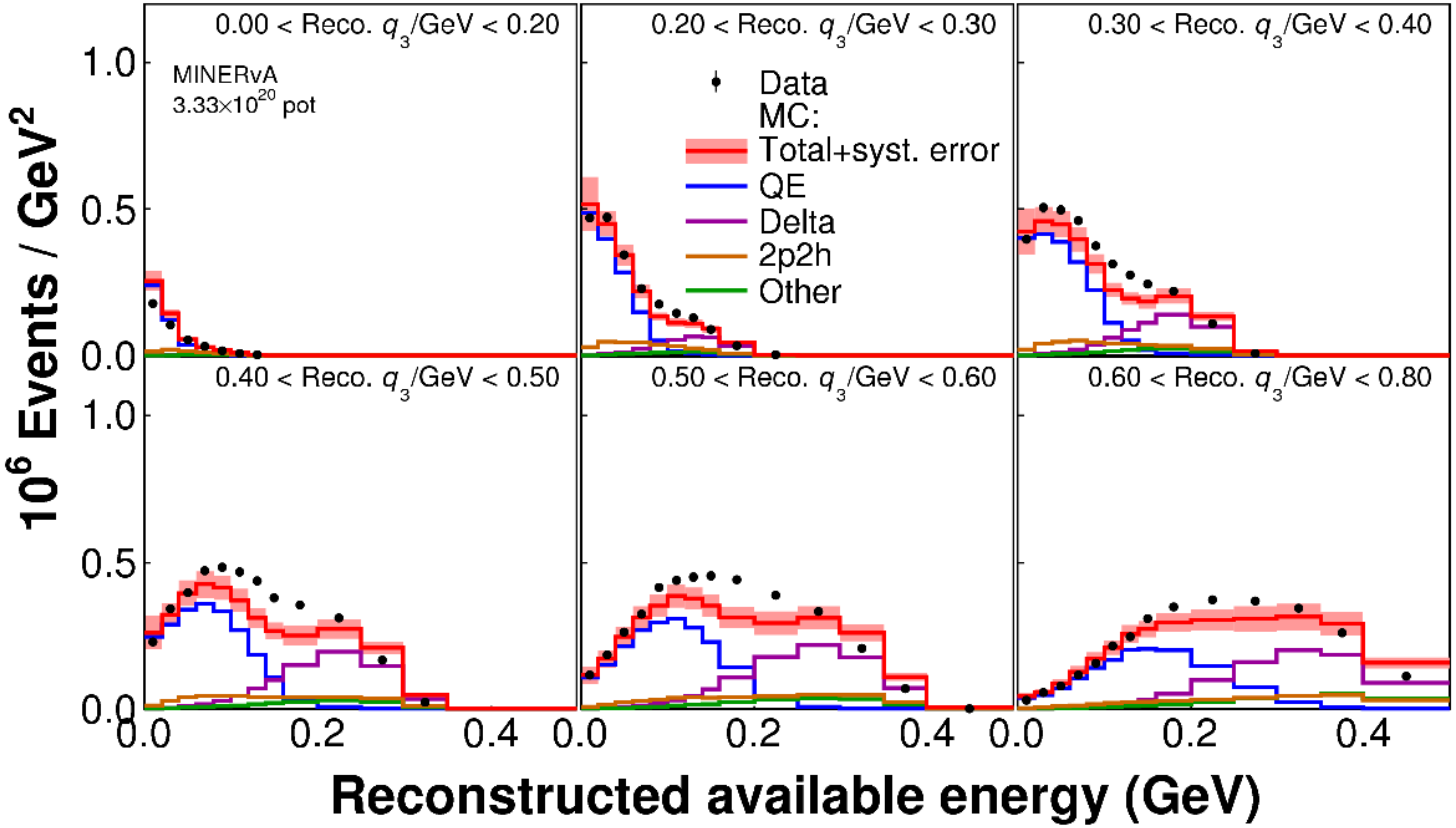
RPA suppression (screening due to W polarization)

Phys. Rev. D ***89****, 073015 (2014)*
Phys. Rev. D ***88****, 113007 (2013)*
arXiv:1601.02038 [hep-ph]
Phys. Rev. C ***70****, 055503 (2004)*

Nucl.Instrum.Meth.A614 (2010) 87-104

P. Rodrigues, Fermilab wine and cheese 11 Dec 2015

Compare the simulation to MINERvA data



(Corresponds to q_0)

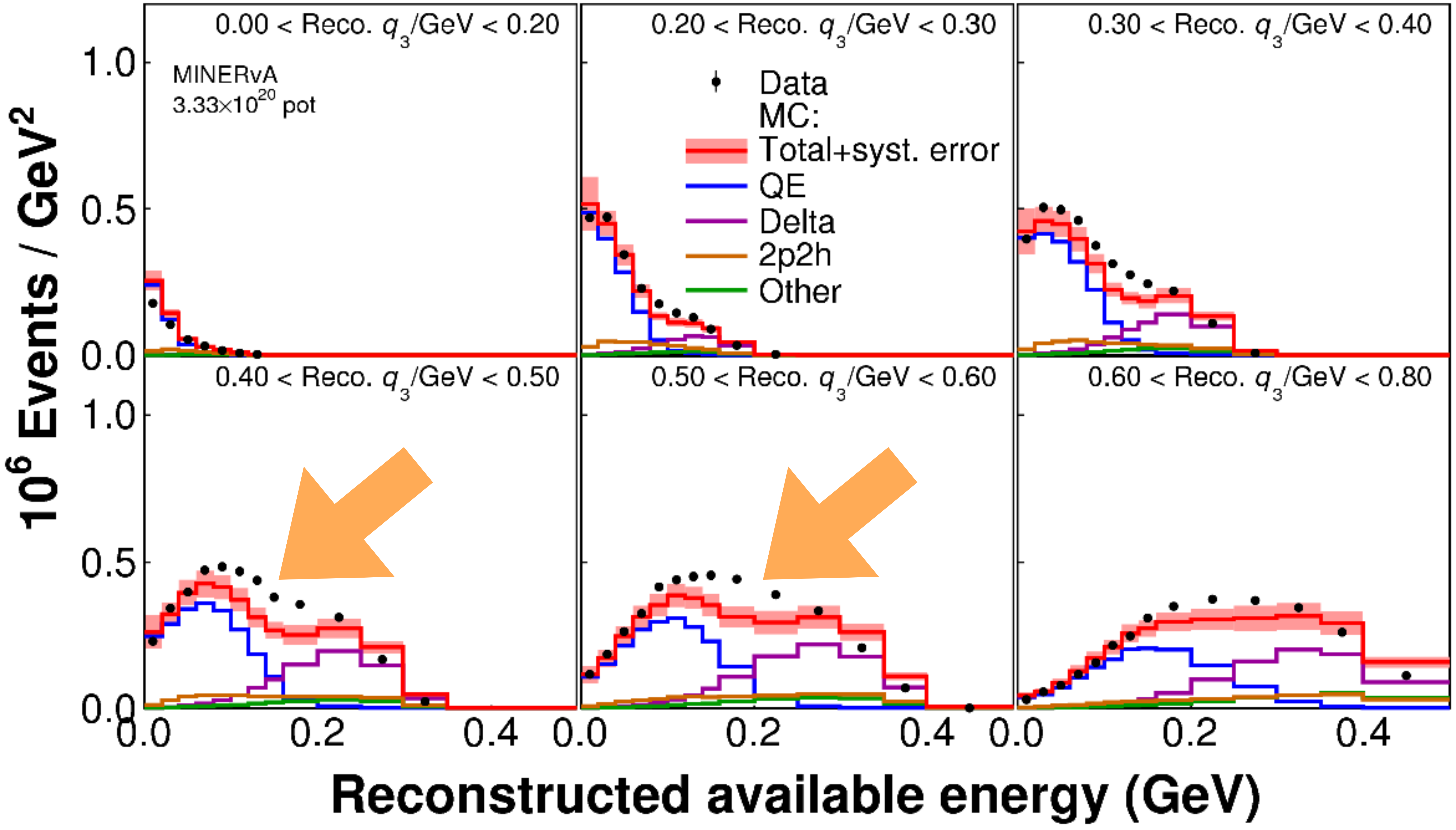
● Data

🟥 Simulation inc. 2p2h

— 2p2h contribution

Each plot is a “slice” through the 2-d distribution

Compare the simulation to MINERvA data



(Corresponds to q_0)

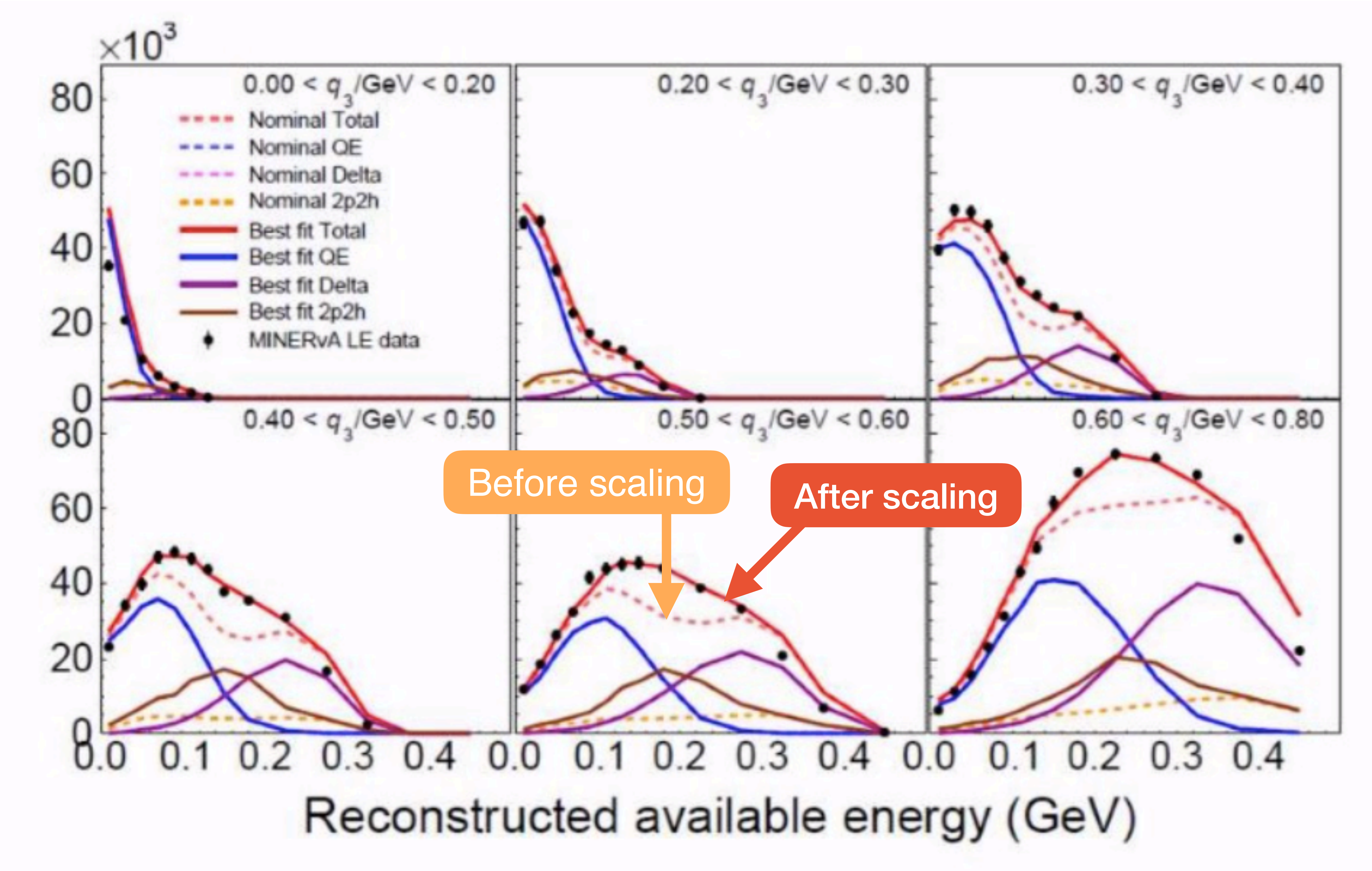
● Data

🟥 Simulation inc. 2p2h

▬ 2p2h contribution

- Including **RPA** and **2p2h** effects improves agreement with MINERvA's data, but it's **not enough**

Compare the simulation to MINERvA data



Before scaling

After scaling

(Corresponds to q_0)

- Including **RPA** and **2p2h** effects improves agreement with MINERvA's data, but it's **not enough**
- **Scale** 2p2h contribution by a 2d Gaussian in q_0-q_3 plane and find **best fit**
- Good fit to the data - but **why?**

Match the interaction to the final state

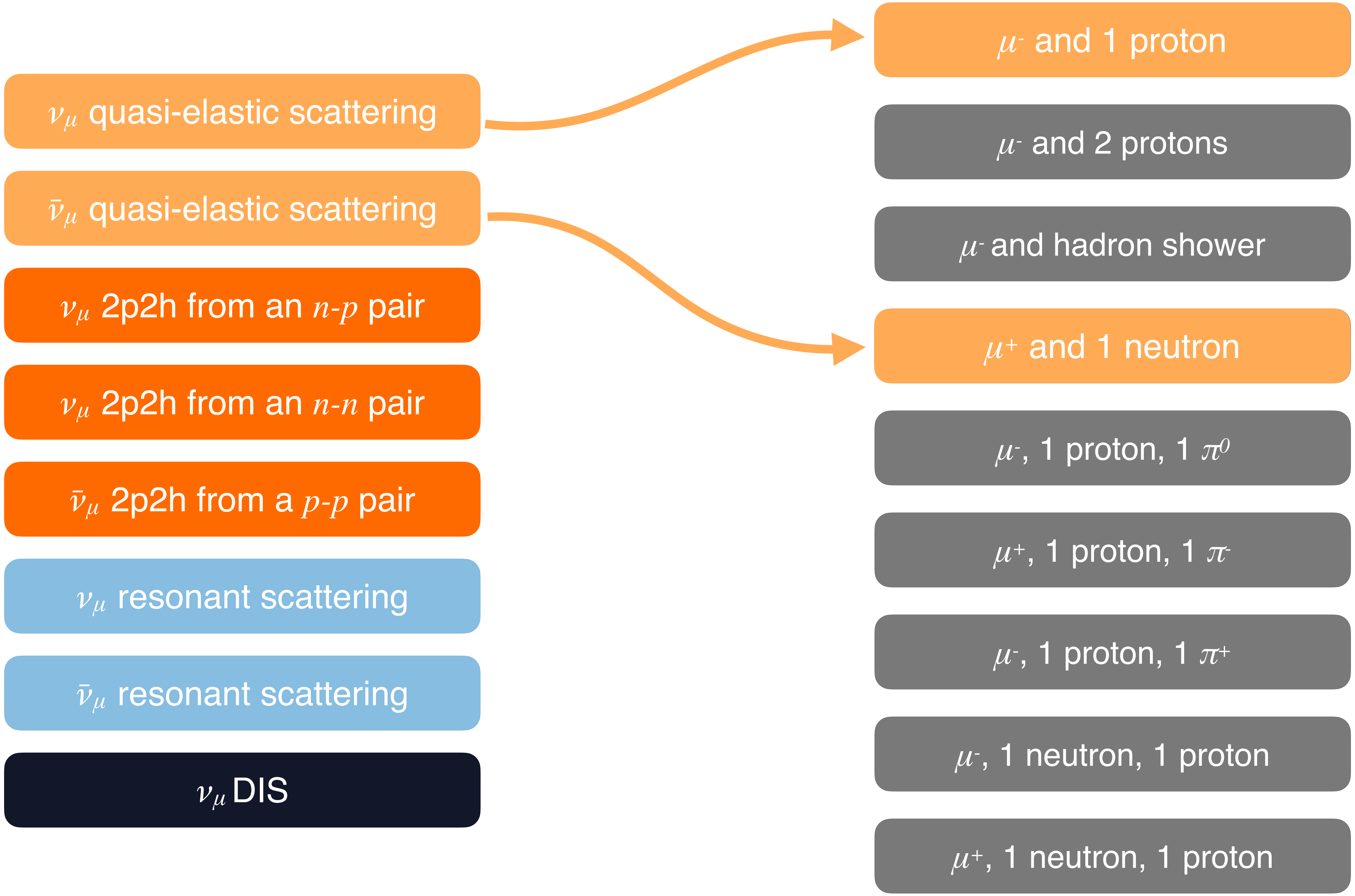
Exercise 6

- ν_μ quasi-elastic scattering
- $\bar{\nu}_\mu$ quasi-elastic scattering
- ν_μ 2p2h from an n-p pair
- ν_μ 2p2h from an n-n pair
- $\bar{\nu}_\mu$ 2p2h from a p-p pair
- ν_μ resonant scattering
- $\bar{\nu}_\mu$ resonant scattering
- ν_μ DIS

- μ^- and 1 proton
- μ^- and 2 protons
- μ^- and hadron shower
- μ^+ and 1 neutron
- μ^-, 1 proton, 1 π^0
- μ^+, 1 proton, 1 π^-
- μ^-, 1 proton, 1 π^+
- μ^-, 1 neutron, 1 proton
- μ^+, 1 neutron, 1 proton

Exercise 6

Match the interaction to the final state



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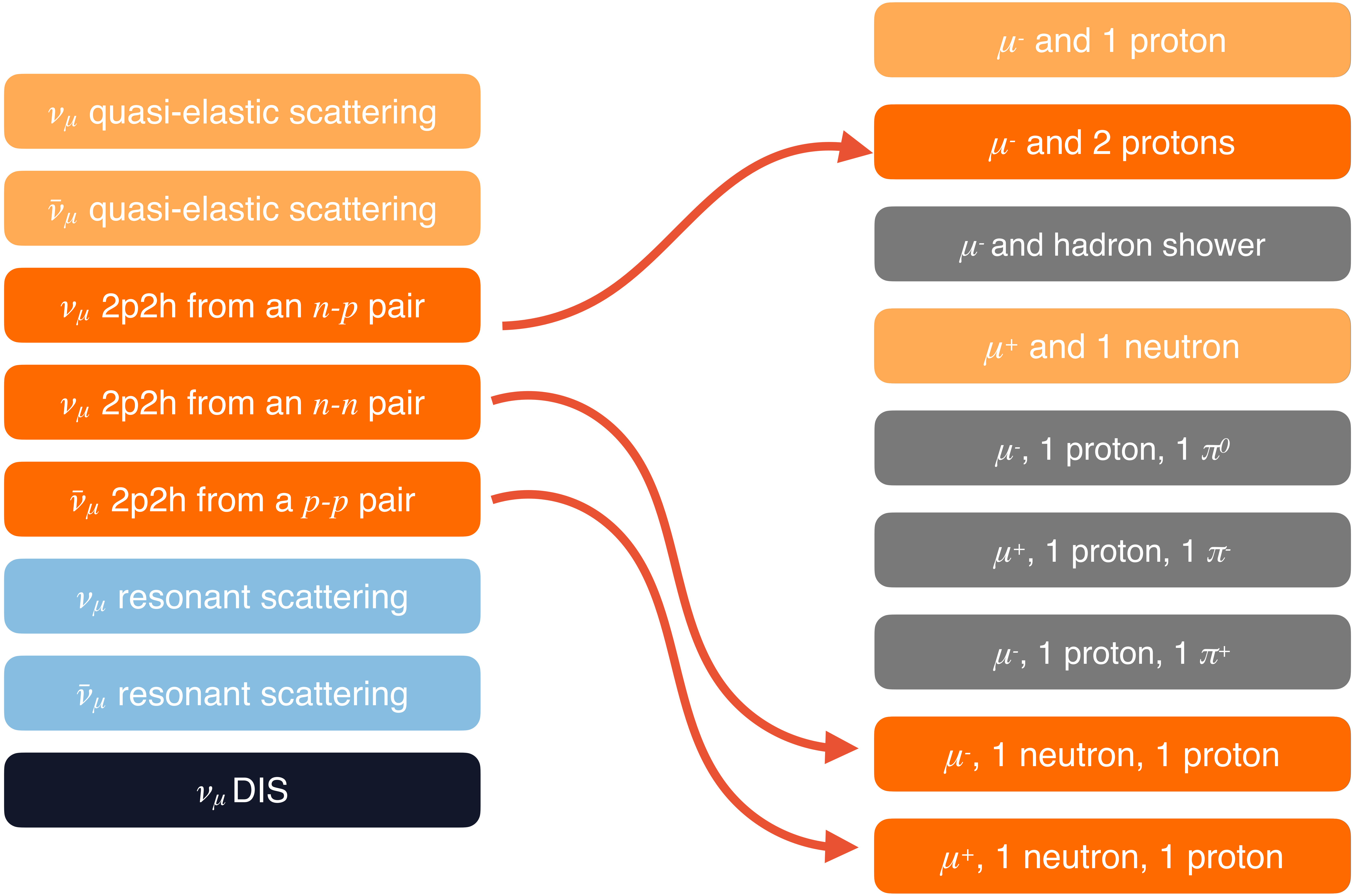
- μ^-, 1 proton, 1 π^+
- μ^-, 1 neutron, 1 proton
- μ^+, 1 neutron, 1 proton

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

Match the interaction to the final state

Exercise 6



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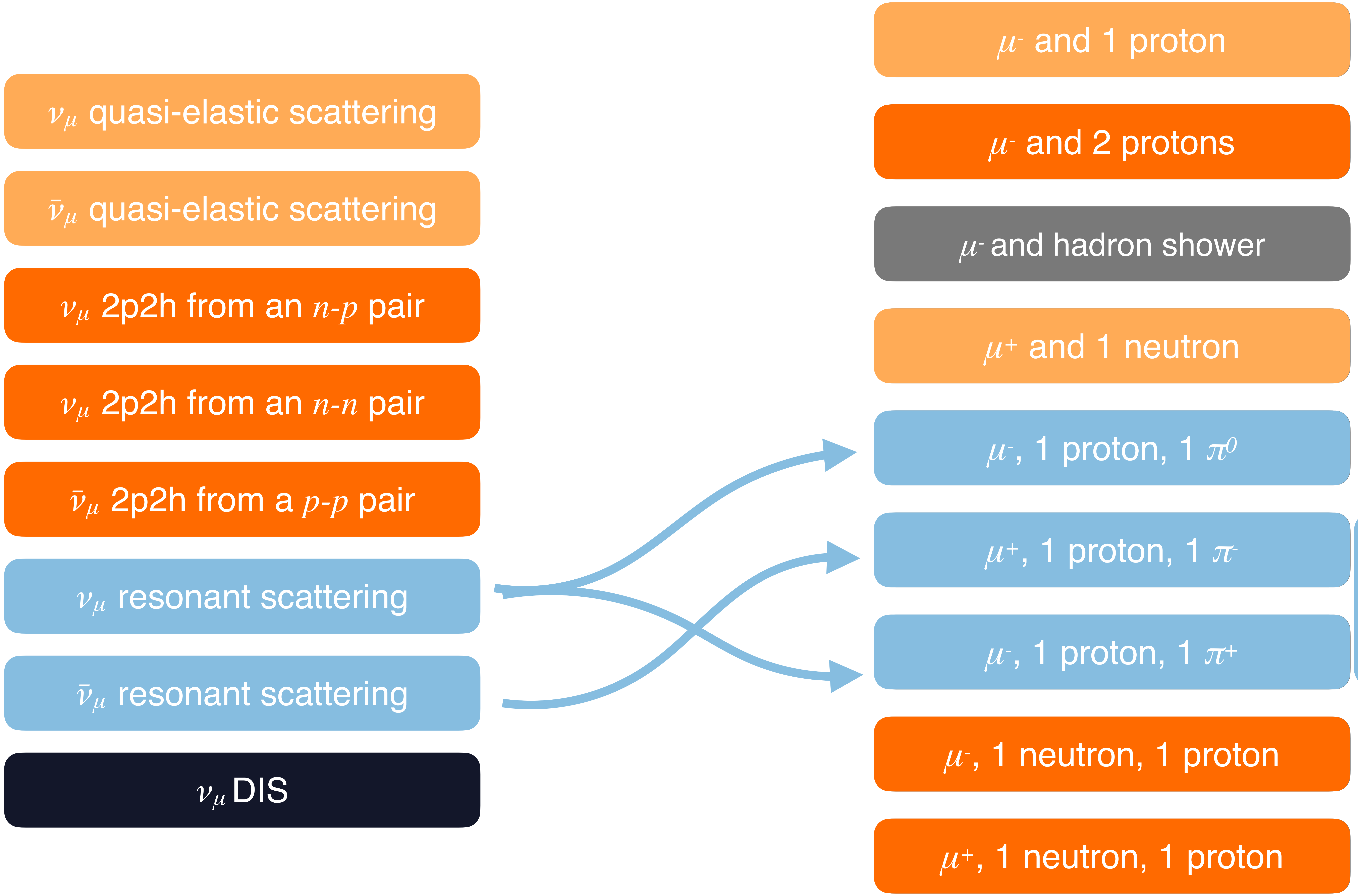
- ν_μ DIS

- μ^- and 1 proton — $\nu_\mu + n \to \mu^- + p$
- μ^- and 2 protons — $\nu_\mu + n(+p) \to \mu^- + p(+p)$
- μ^- and hadron shower
- μ^+ and 1 neutron — $\bar{\nu}_\mu + p \to \mu^+ + n$
- μ^-, 1 proton, 1 π^0
- μ^+, 1 proton, 1 π^-
- μ^-, 1 proton, 1 π^+
- μ^-, 1 neutron, 1 proton — $\nu_\mu + n(+n) \to \mu^- + p(+n)$
- μ^+, 1 neutron, 1 proton — $\bar{\nu}_\mu + p(+p) \to \mu^+ + n(+p)$

What if you can't tell the muon charge?

Match the interaction to the final state

Exercise 6



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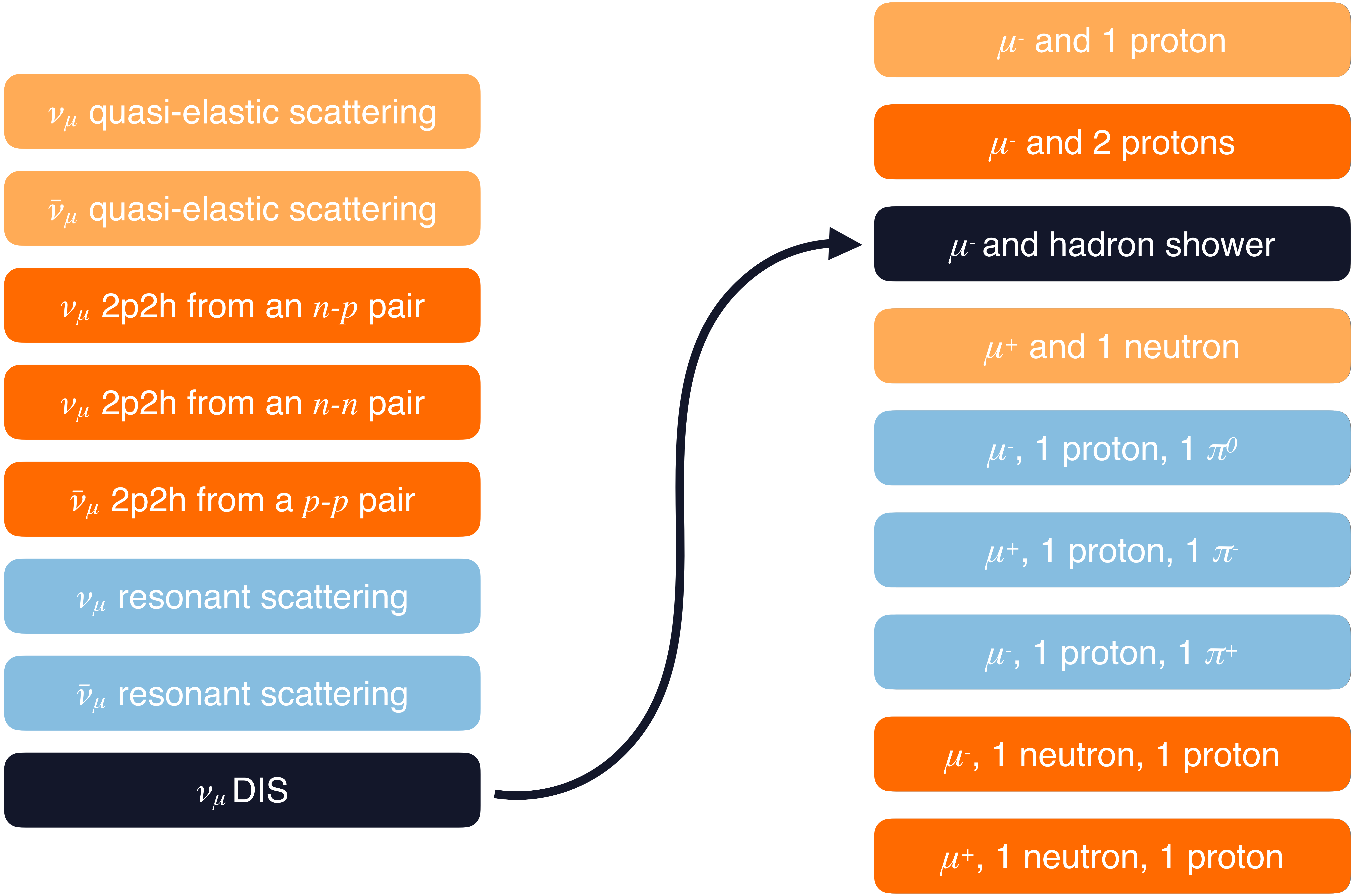
- $\bar{\nu}_\mu$ resonant scattering
- ν_μ DIS

μ^- and 1 proton	$\nu_\mu + n \to \mu^- + p$
μ^- and 2 protons	$\nu_\mu + n(+p) \to \mu^- + p(+p)$
μ^- and hadron shower	
μ^+ and 1 neutron	
μ^-, 1 proton, 1 π^0	$\nu_\mu + n \to \mu^- + \Delta^+ \to \mu^- + p + \pi^0$
μ^+, 1 proton, 1 π^-	$\bar{\nu}_\mu + p \to \mu^+ + \Delta^0 \to \mu^+ + p + \pi^-$
μ^-, 1 proton, 1 π^+	$\nu_\mu + p \to \mu^- + \Delta^{++} \to \mu^- + p + \pi^+$
μ^-, 1 neutron, 1 proton	$\nu_\mu + n(+n) \to \mu^- + p(+n)$
μ^+, 1 neutron, 1 proton	$\bar{\nu}_\mu + p(+p) \to \mu^+ + n(+p)$

What if you can't tell muon or pion charge?

Match the interaction to the final state

Exercise 6



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μ^- and 1 proton	$\nu_\mu + n \rightarrow \mu^- + p$
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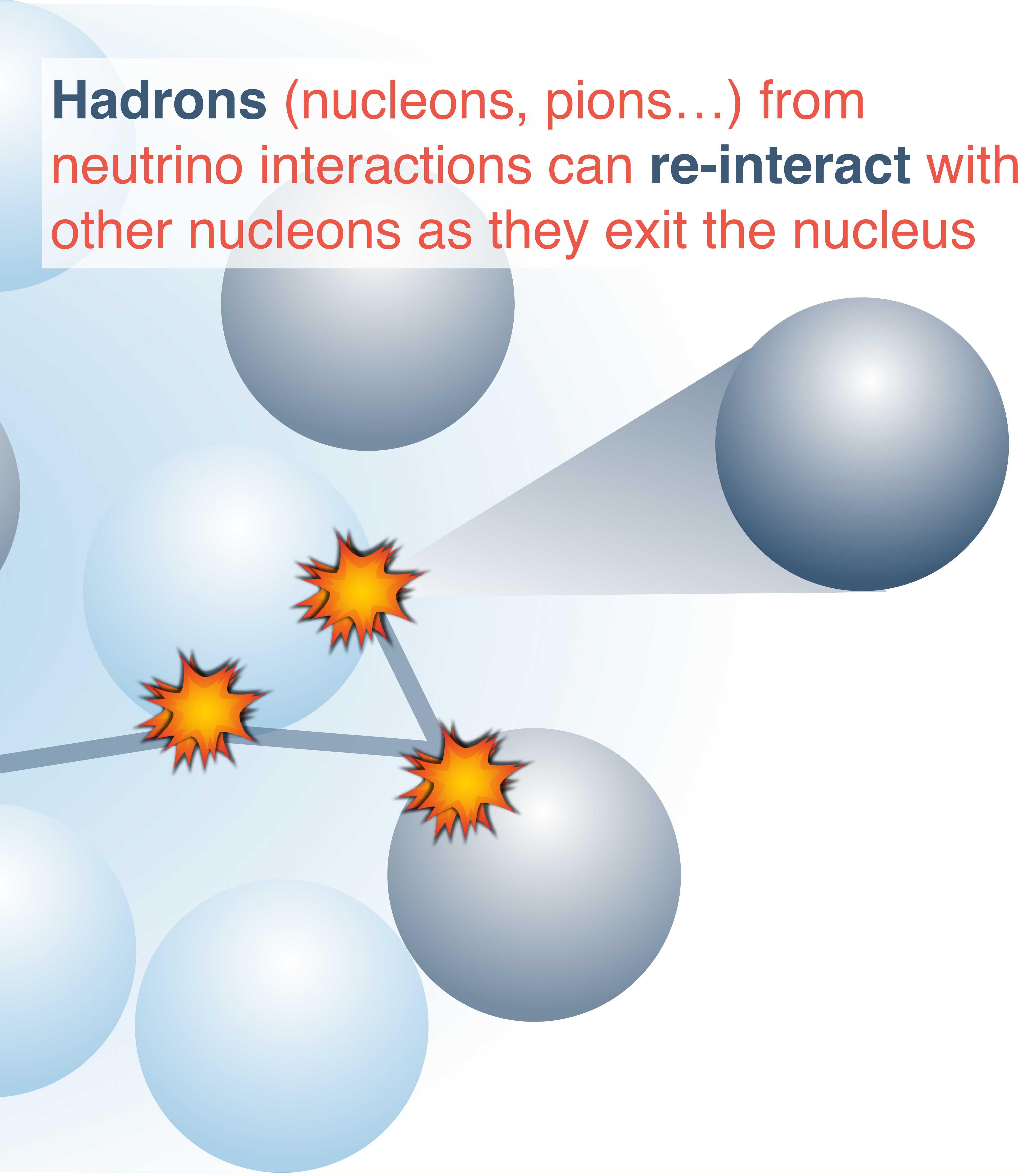
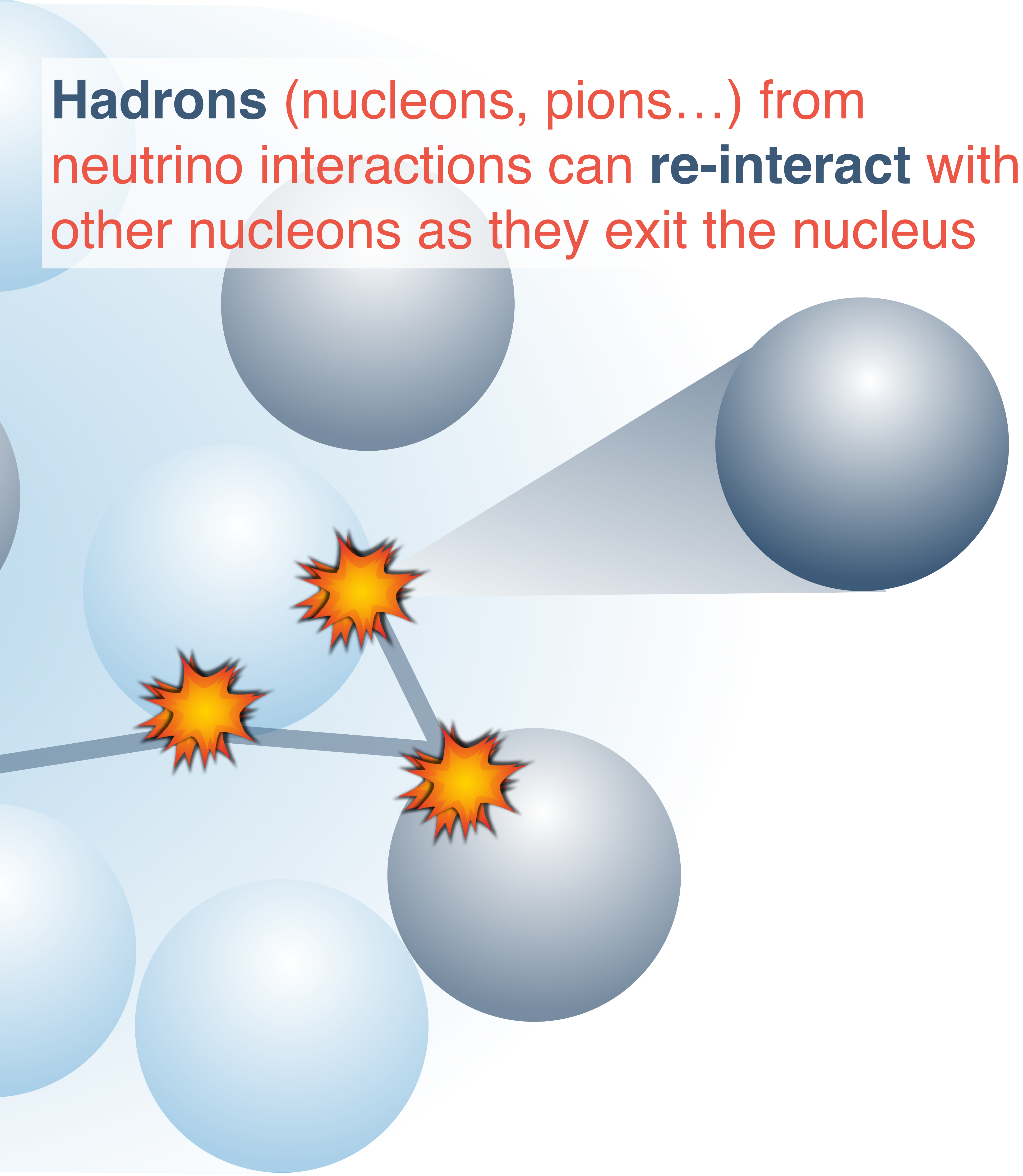
μ^+ and 1 neutron	$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
μ^-, 1 proton, 1 π^0	$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + p + \pi^0$
μ^+, 1 proton, 1 π^-	$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^0 \rightarrow \mu^+ + p + \pi^-$
μ^-, 1 proton, 1 π^+	$\nu_\mu + p \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+$
μ^-, 1 neutron, 1 proton	$\nu_\mu + n(+n) \rightarrow \mu^- + p(+n)$
μ^+, 1 neutron, 1 proton	$\bar{\nu}_\mu + p(+p) \rightarrow \mu^+ + n(+p)$

How it all goes wrong: final-state interactions

Hadrons (nucleons, pions…) from neutrino interactions can **re-interact** with other nucleons as they exit the nucleus



How it all goes wrong: final-state interactions



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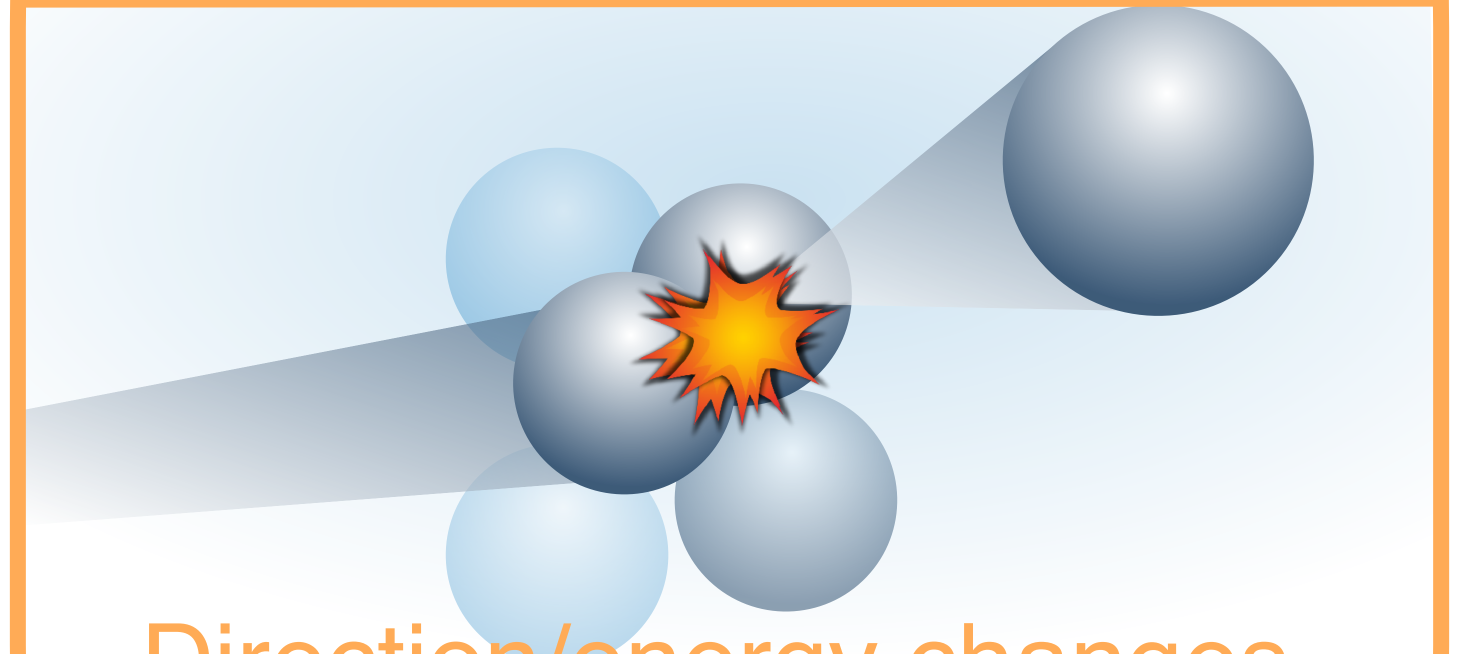
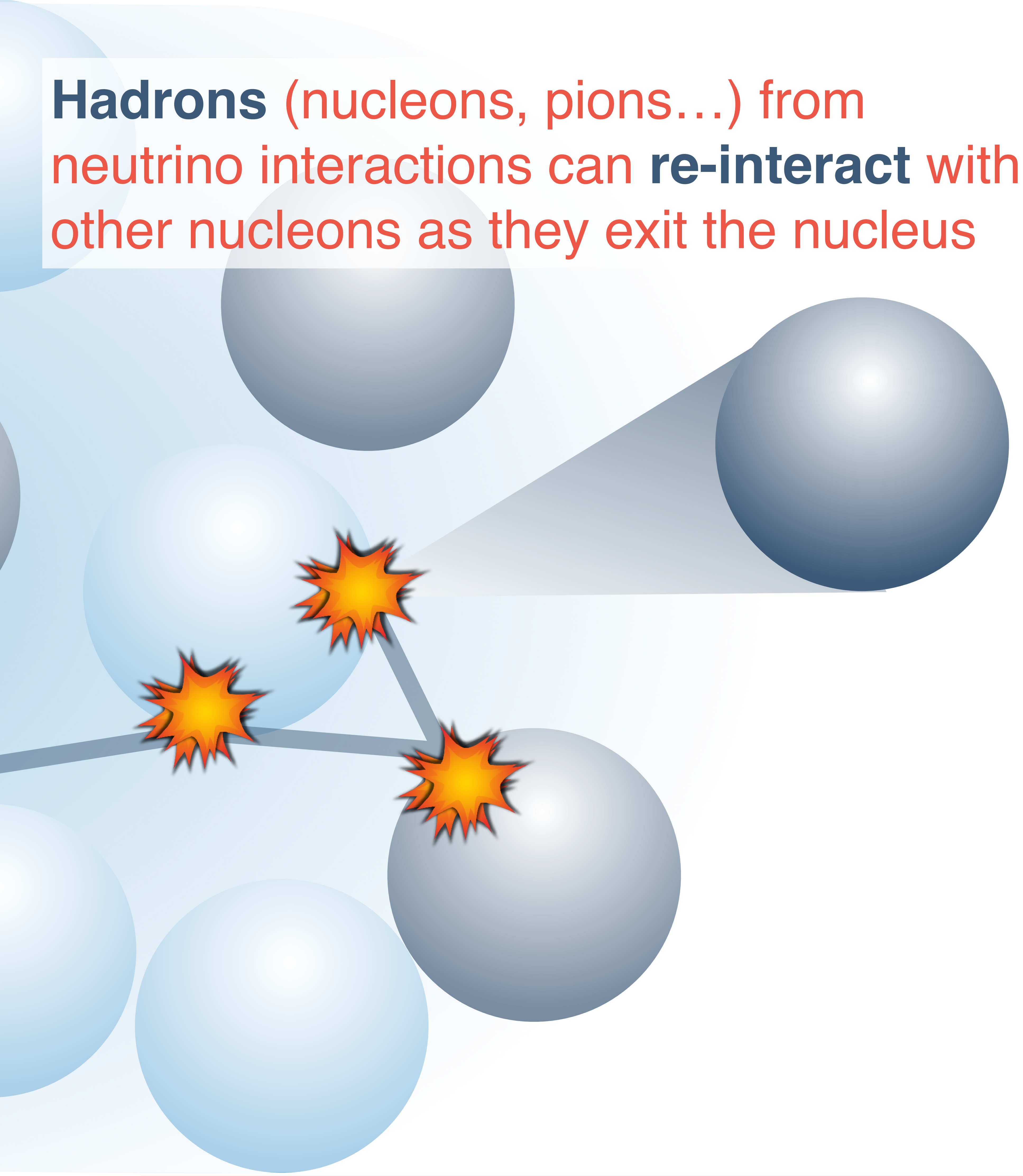
Elastic scattering



Direction/energy changes, nucleon knock-out

How it all goes wrong: final-state interactions



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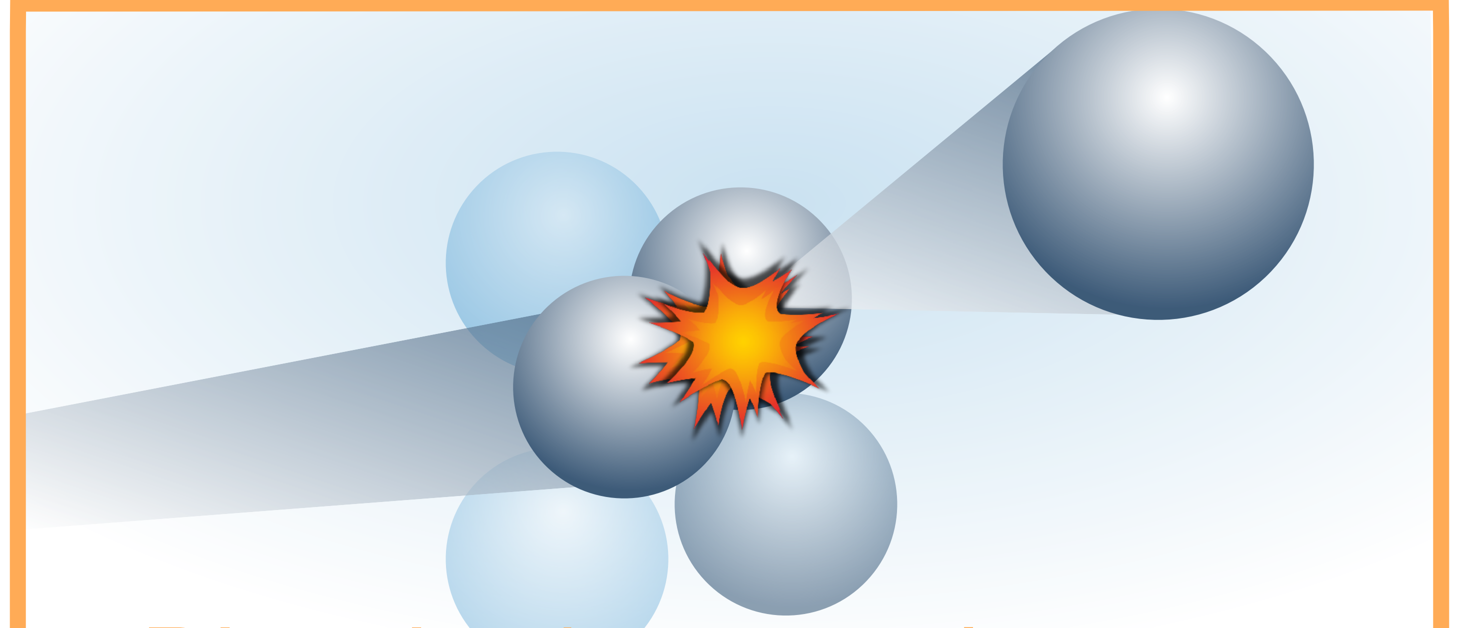
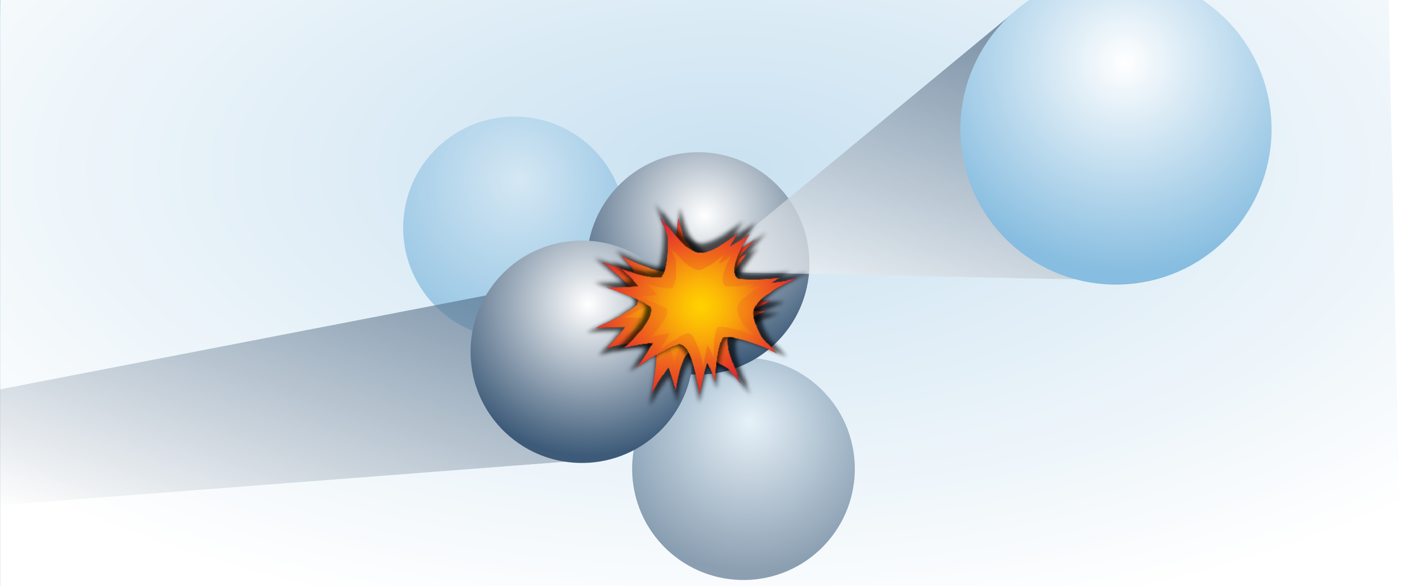


Direction/energy changes, nucleon knock-out

Charge exchange

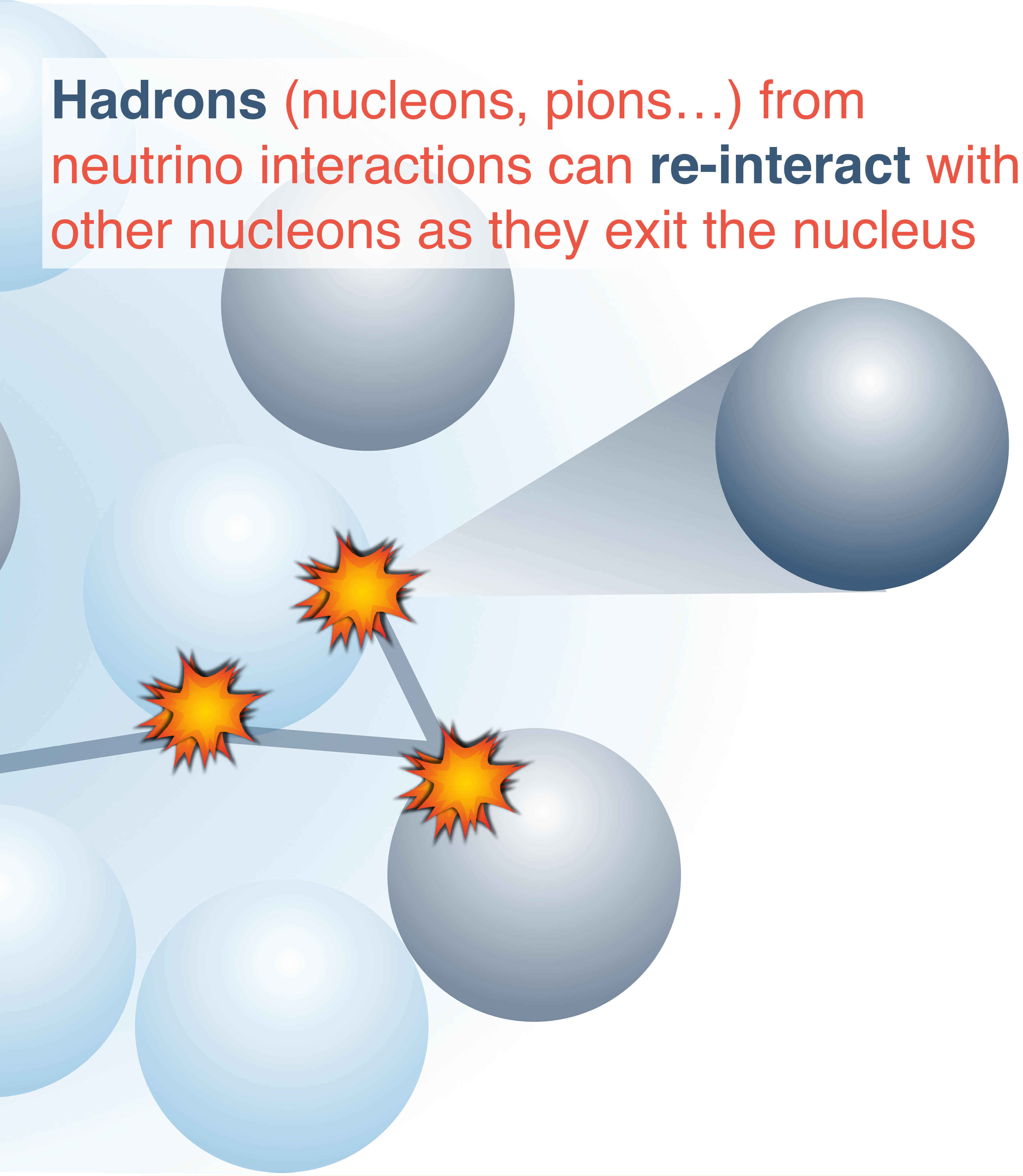


neutron ⟷ proton

$\pi^{+} \longleftrightarrow \pi^{0} \longleftrightarrow \pi^{-}$

How it all goes wrong: final-state interactions

Hadrons (nucleons, pions…) from neutrino interactions can **re-interact** with other nucleons as they exit the nucleus



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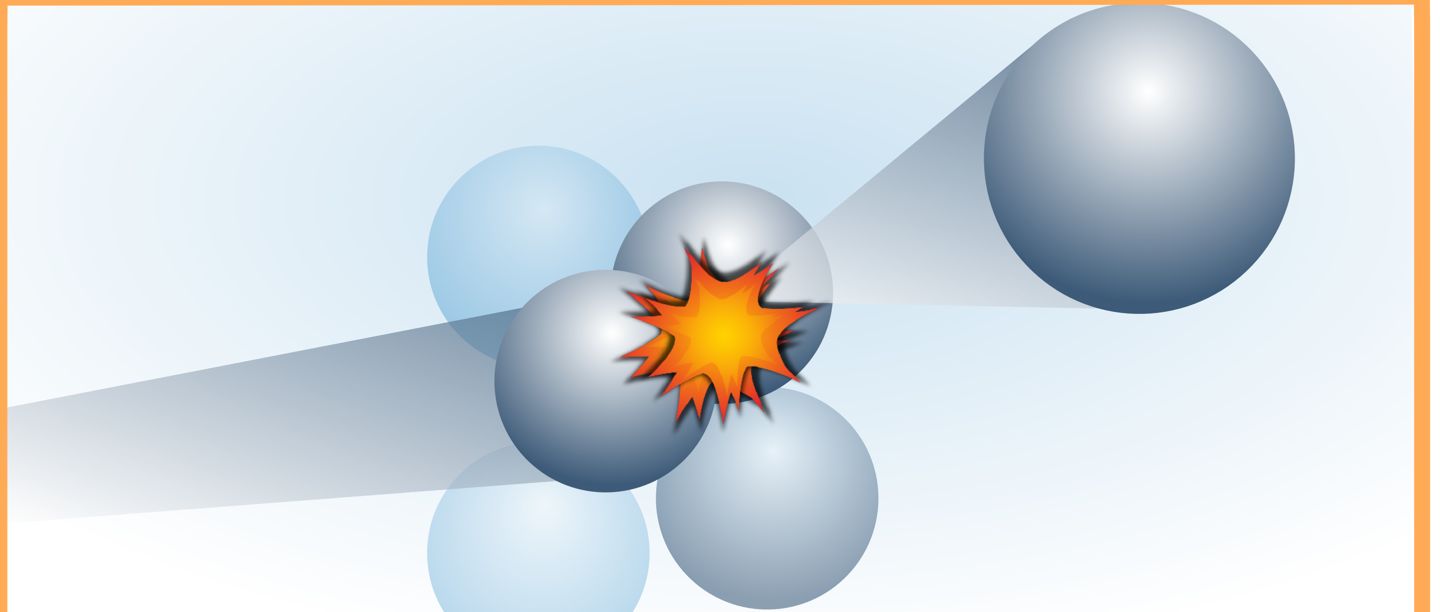

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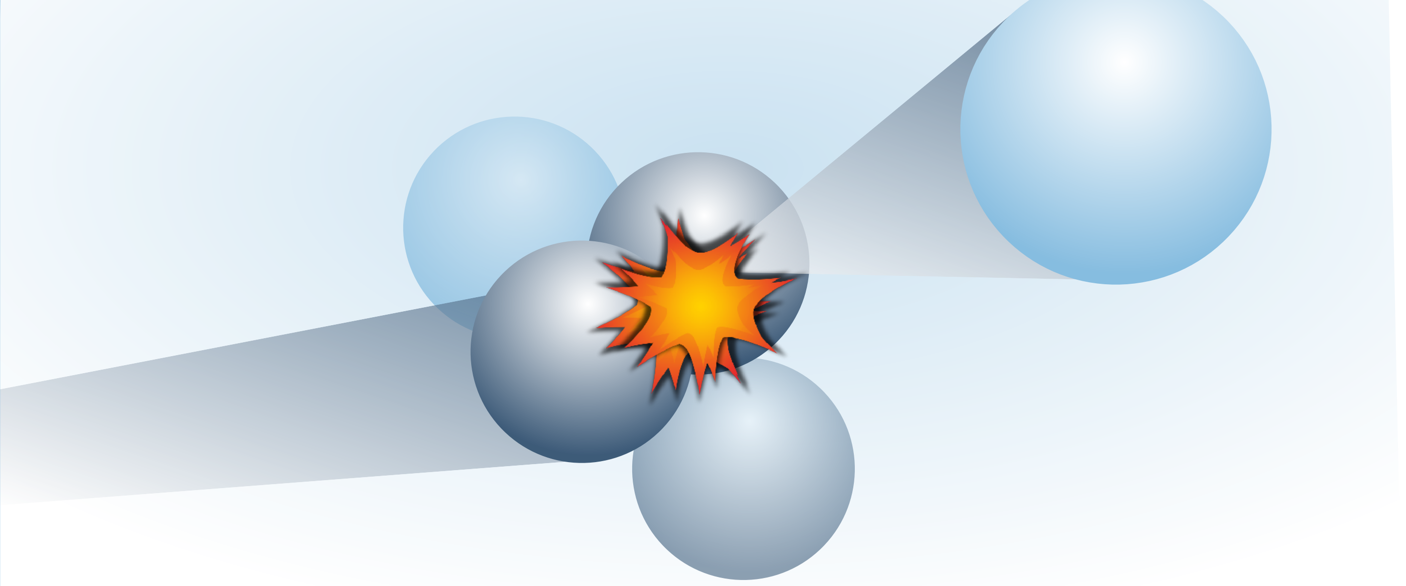
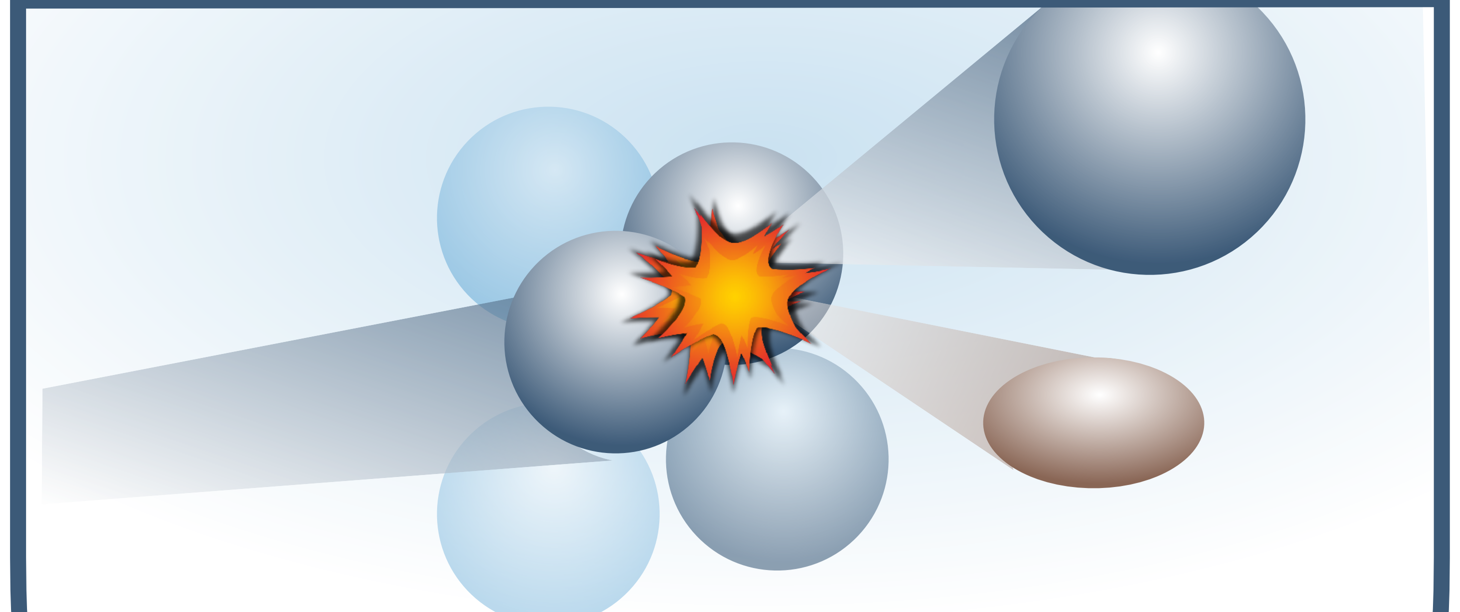


neutron ⟷ proton

$\pi^+ \longleftrightarrow \pi^0 \longleftrightarrow \pi^-$

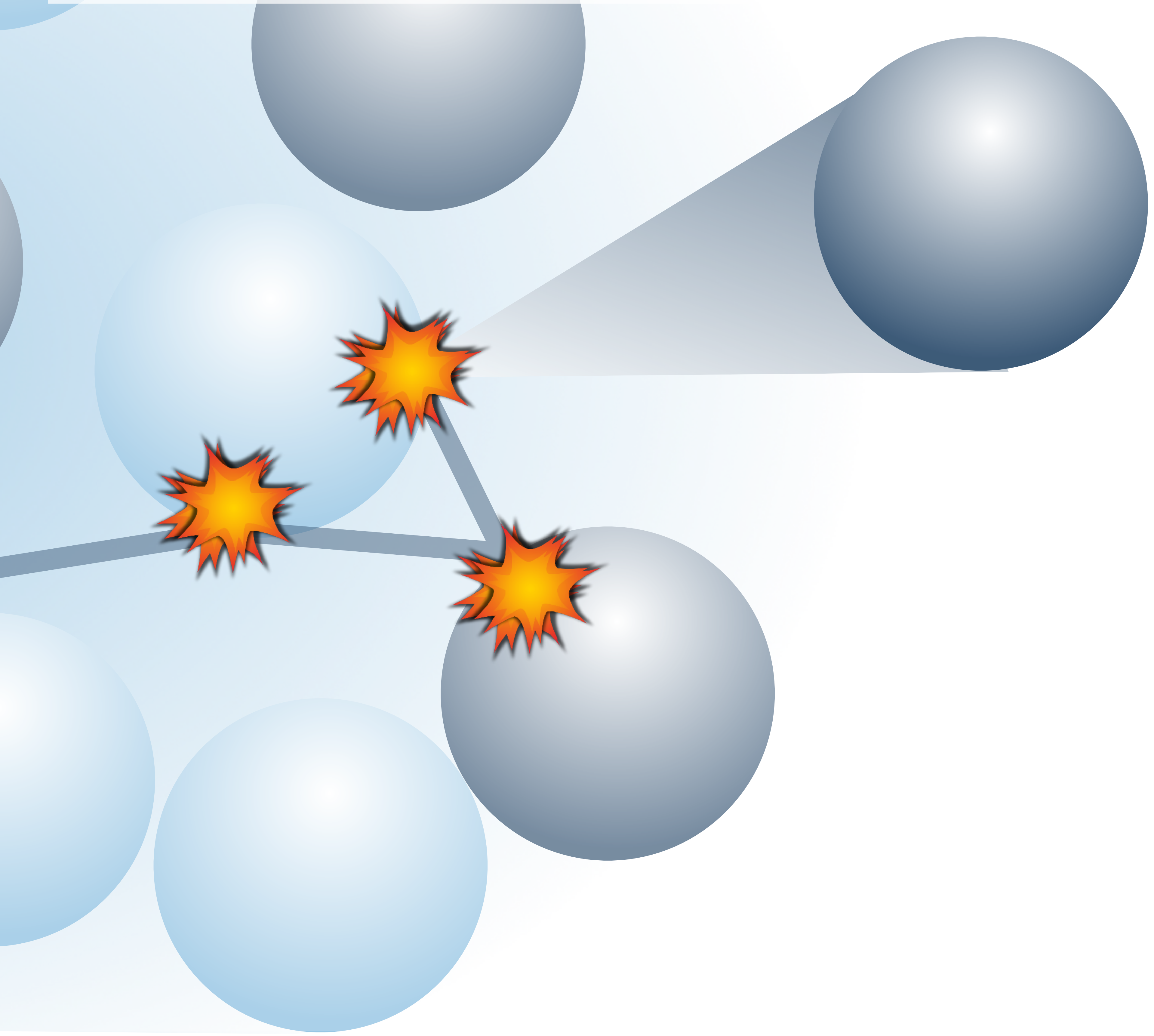
Pion production/ absorption



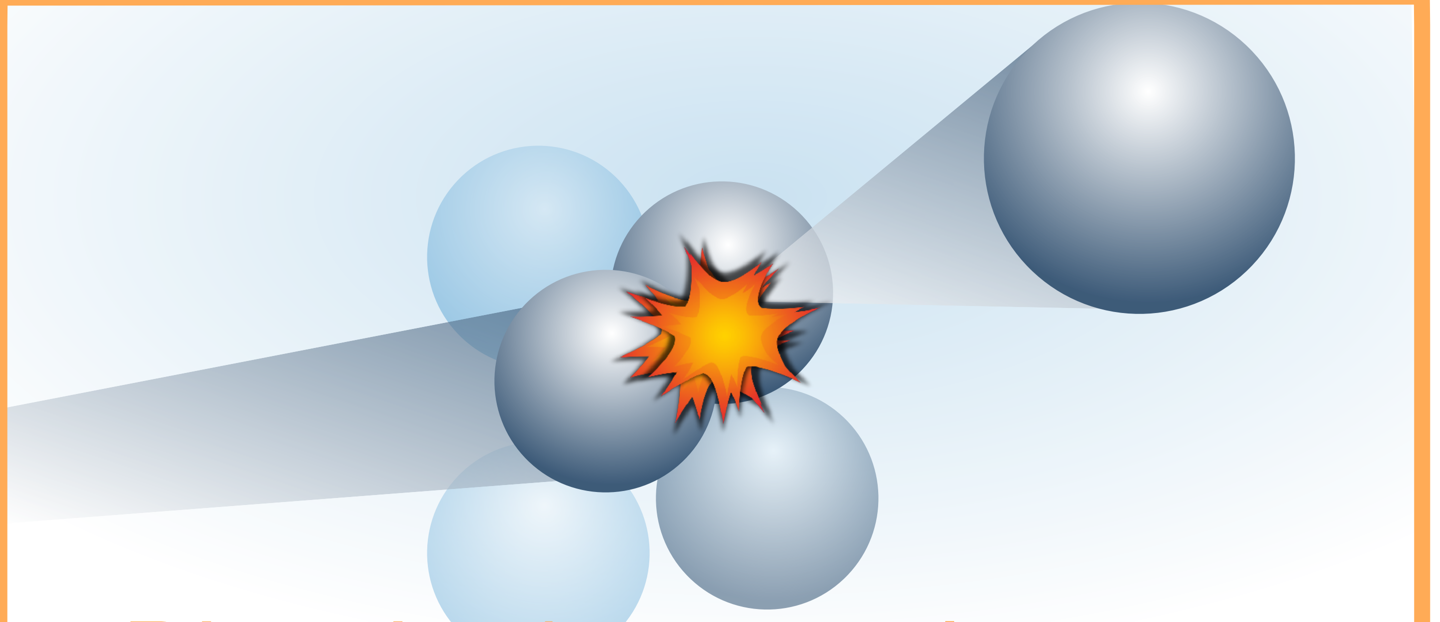
π^+ / π^0 / π^- created / absorbed

How it all goes wrong: final-state interactions

Hadrons (nucleons, pions…) from neutrino interactions can **re-interact** with other nucleons as they exit the nucleus

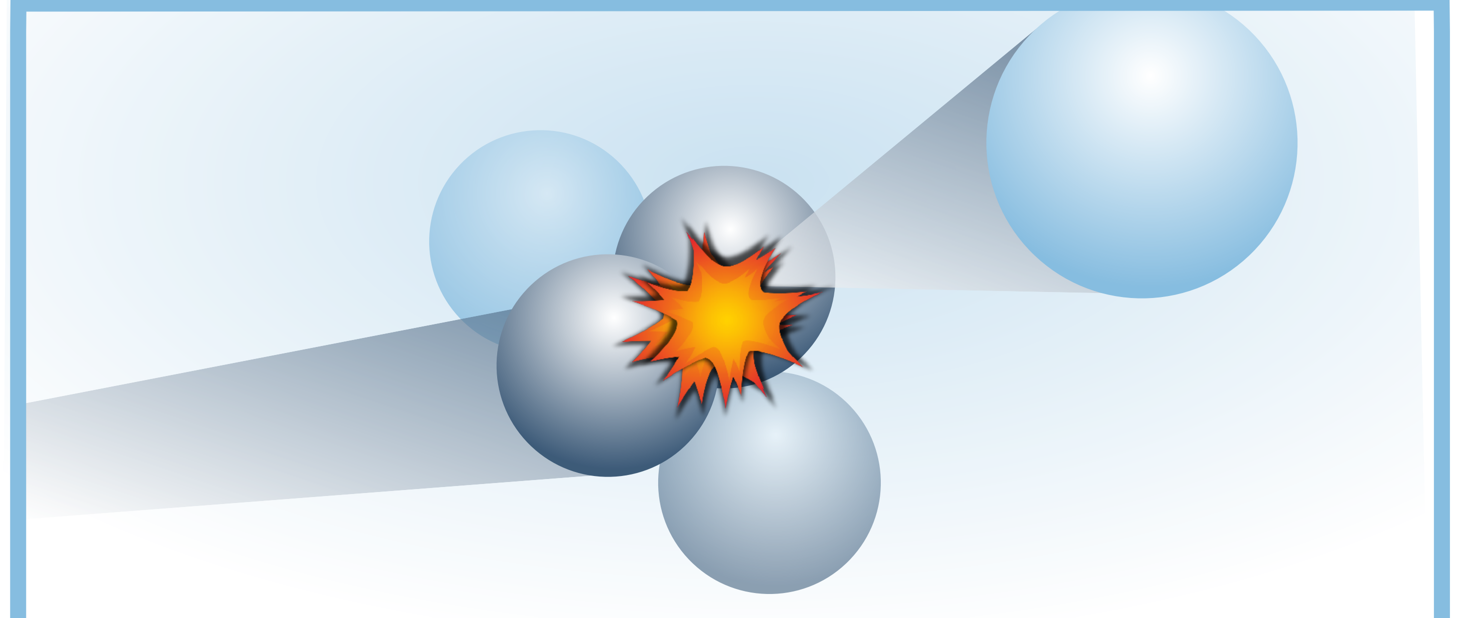


Elastic scattering



Direction/energy changes, nucleon knock-out

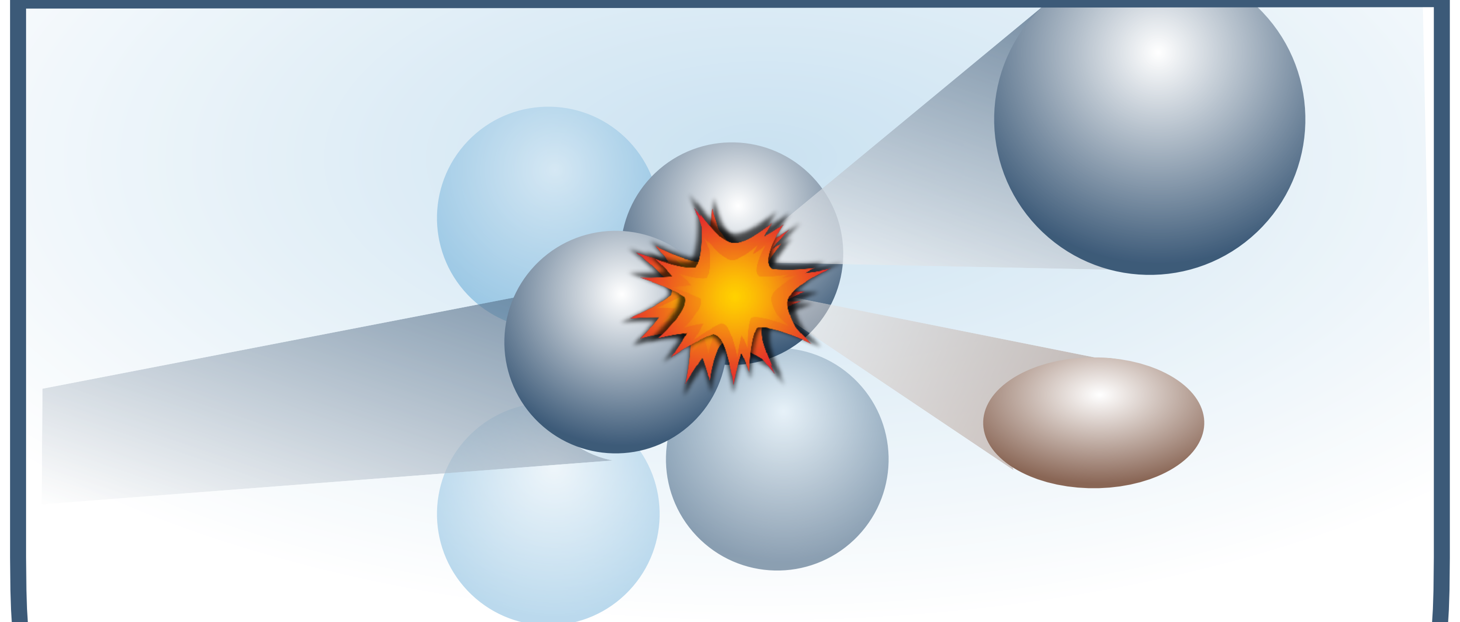
Charge exchange



neutron ⟷ proton

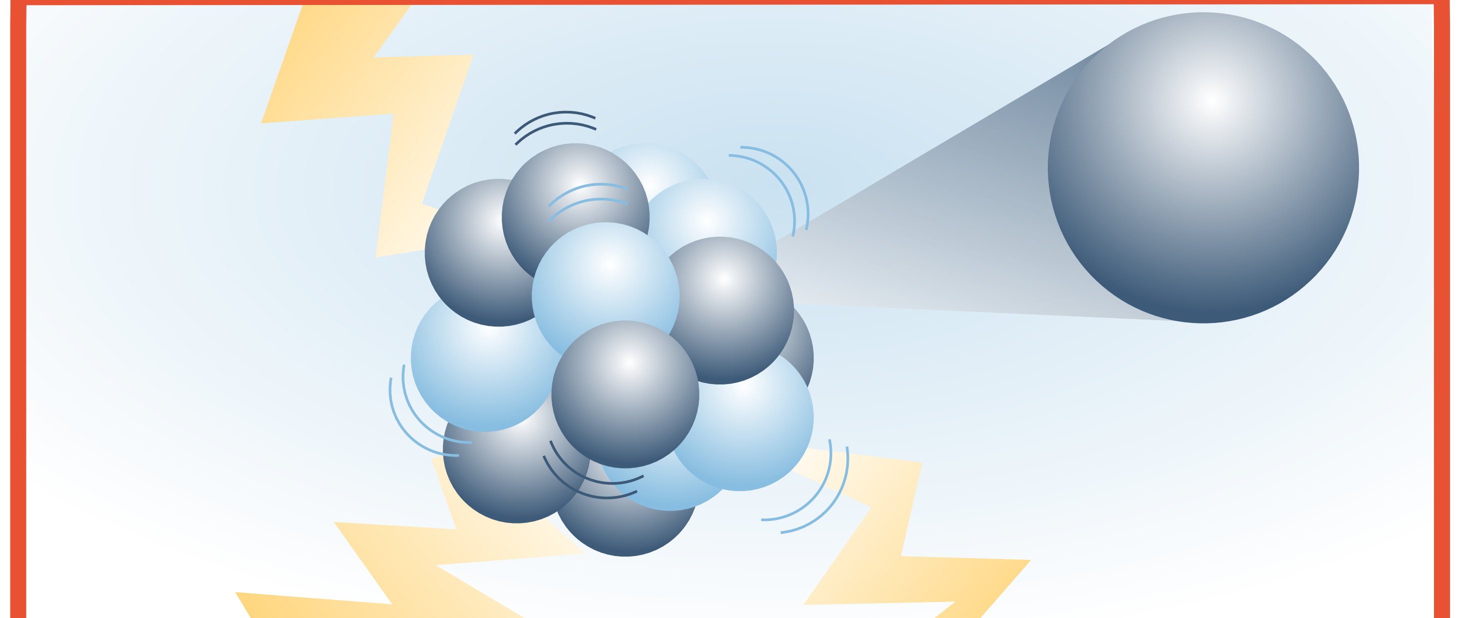
$\pi^+ \longleftrightarrow \pi^0 \longleftrightarrow \pi^-$

Pion production/ absorption



π^+ / π^0 / π^- created / absorbed

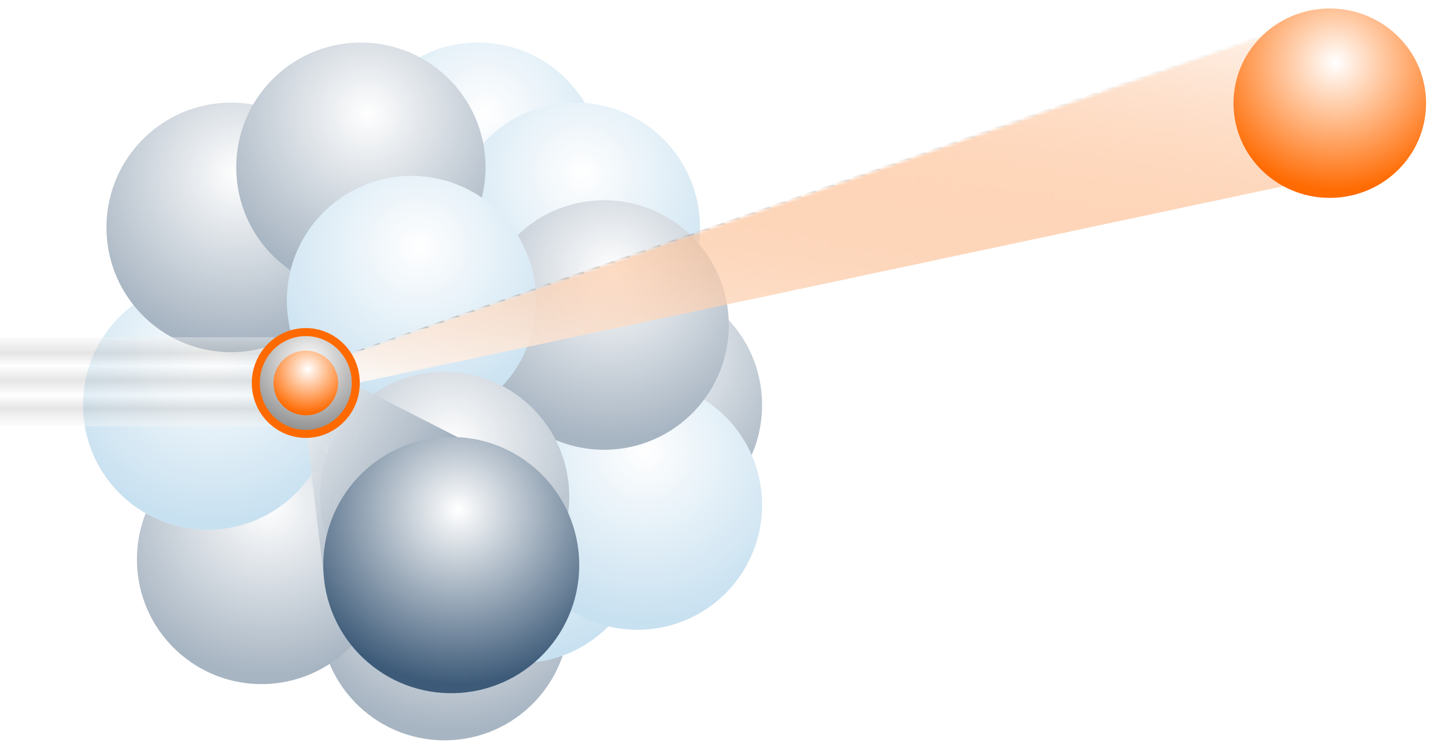
Nuclear de-excitation



Photons produced as struck nucleons de-excite

FSI makes one interaction mode fake another

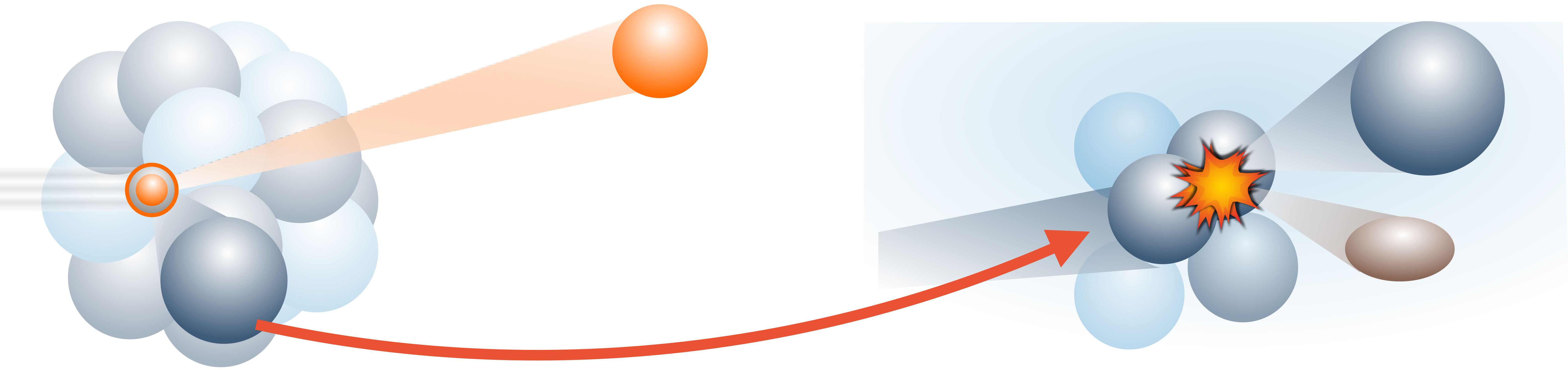
Quasi-elastic scattering



$$\nu_\mu + n \rightarrow \mu^- + p$$

FSI makes one interaction mode fake another

Quasi-elastic scattering plus Pion production FSI



$$\nu_\mu + n \to \mu^- + p \quad +\pi^0$$

FSI makes one interaction mode fake another

Quasi-elastic scattering plus Pion production FSI fakes Resonant pion production

$$\nu_\mu + n \to \mu^- + p \quad +\pi^0$$

$$\nu_\mu + n \to \mu^- + \Delta^+ \to \mu^- + p + \pi^0$$

Match interaction to final state - extreme mode!

Exercise 7

ν_μ quasi-elastic scattering

$\bar{\nu}_\mu$ quasi-elastic scattering

ν_μ resonant scattering

$\bar{\nu}_\mu$ resonant scattering

ν_μ MEC

No FSI

Elastic scattering

Charge exchange

Pion production

Pion absorption

Nuclear de-excitation

μ^- + proton

Muon (charge unknown) + 1 proton

μ^- + 2 protons

μ^- + neutron + π^+

μ^- + proton + photons

Match interaction to final state - extreme mode!

μ^- + proton

Match interaction to final state - extreme mode!

ν_μ quasi-elastic scattering

No FSI

μ^- + proton

Match interaction to final state - extreme mode!

ν_μ quasi-elastic scattering

ν_μ resonant scattering

No FSI

Pion absorption

μ^- + proton

Match interaction to final state - extreme mode!

Muon (charge unknown) + 1 proton

Match interaction to final state - extreme mode!

ν_μ quasi-elastic scattering

No FSI

Muon (charge unknown) + 1 proton

ν_μ resonant scattering

Pion absorption

Match interaction to final state - extreme mode!

ν_μ quasi-elastic scattering

ν_μ resonant scattering

$\bar{\nu}_\mu$ resonant scattering

$\bar{\nu}_\mu$ quasi-elastic scattering

No FSI

Pion absorption

Pion absorption

Charge exchange

Muon (charge unknown) + 1 proton

If we don't know the muon charge, antineutrino scattering starts to fake neutrino scattering

Match interaction to final state - extreme mode!

μ^- + 2 protons

Match interaction to final state - extreme mode!

ν_μ MEC

No FSI

μ^- + 2 protons

Match interaction to final state - extreme mode!

ν_μ MEC

ν_μ quasi-elastic scattering

No FSI

Elastic scattering

μ^- + 2 protons

Additional low-energy nucleons can be knocked out

Match interaction to final state - extreme mode!

ν_μ MEC

ν_μ quasi-elastic scattering

ν_μ resonant scattering

No FSI

Elastic scattering

Pion absorption

μ^- + 2 protons

Additional low-energy nucleons can be knocked out

Pion absorption frequently knocks out additional nucleons

Match interaction to final state - extreme mode!

ν_μ resonant scattering

No FSI

μ^- + neutron + π^+

Match interaction to final state - extreme mode!

ν_μ resonant scattering

ν_μ quasi-elastic scattering

No FSI

Pion production

Charge exchange

μ^- + neutron + π^+

One interaction can involve more than one FSI. This is increasingly likely for heavier nuclei.

Match interaction to final state - extreme mode!

μ^- + proton + photons

Match interaction to final state - extreme mode!

ν_μ resonant scattering

Pion absorption

Nuclear de-excitation

μ^- + proton + photons

ν_μ quasi-elastic scattering

Elastic scattering

Nuclear de-excitation

De-excitation happens after other FSI, producing additional gammas.

Match interaction to final state - extreme mode!

ν_μ resonant scattering

Pion absorption

Nuclear de-excitation

μ^- + proton + photons

ν_μ quasi-elastic scattering

Elastic scattering

Nuclear de-excitation

De-excitation happens after other FSI, producing additional gammas.

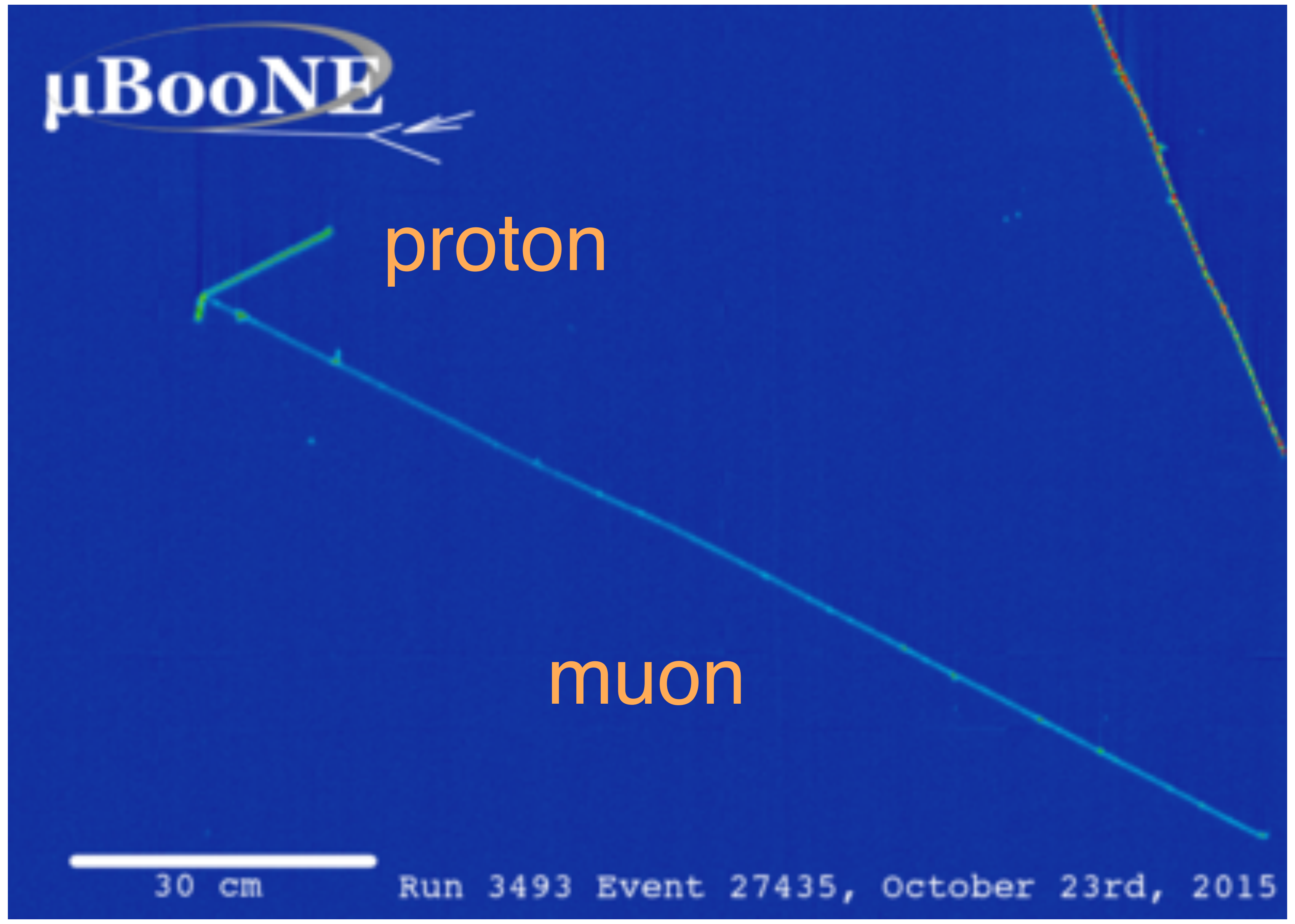
ν_μ resonant scattering

No FSI

A π^0 decays to two photons, so this could be the decay of $\Delta^+ \rightarrow p\ \pi^0 \rightarrow p\ \gamma\gamma$

Summary - consequences of FSI

- FSI “fakers” make it hard to identify a sample of events corresponding to a single interaction mode (**exclusive sample**).
- This is particularly hard if your **detector** gives limited information (no muon/pion charges, poor low-energy detection etc)

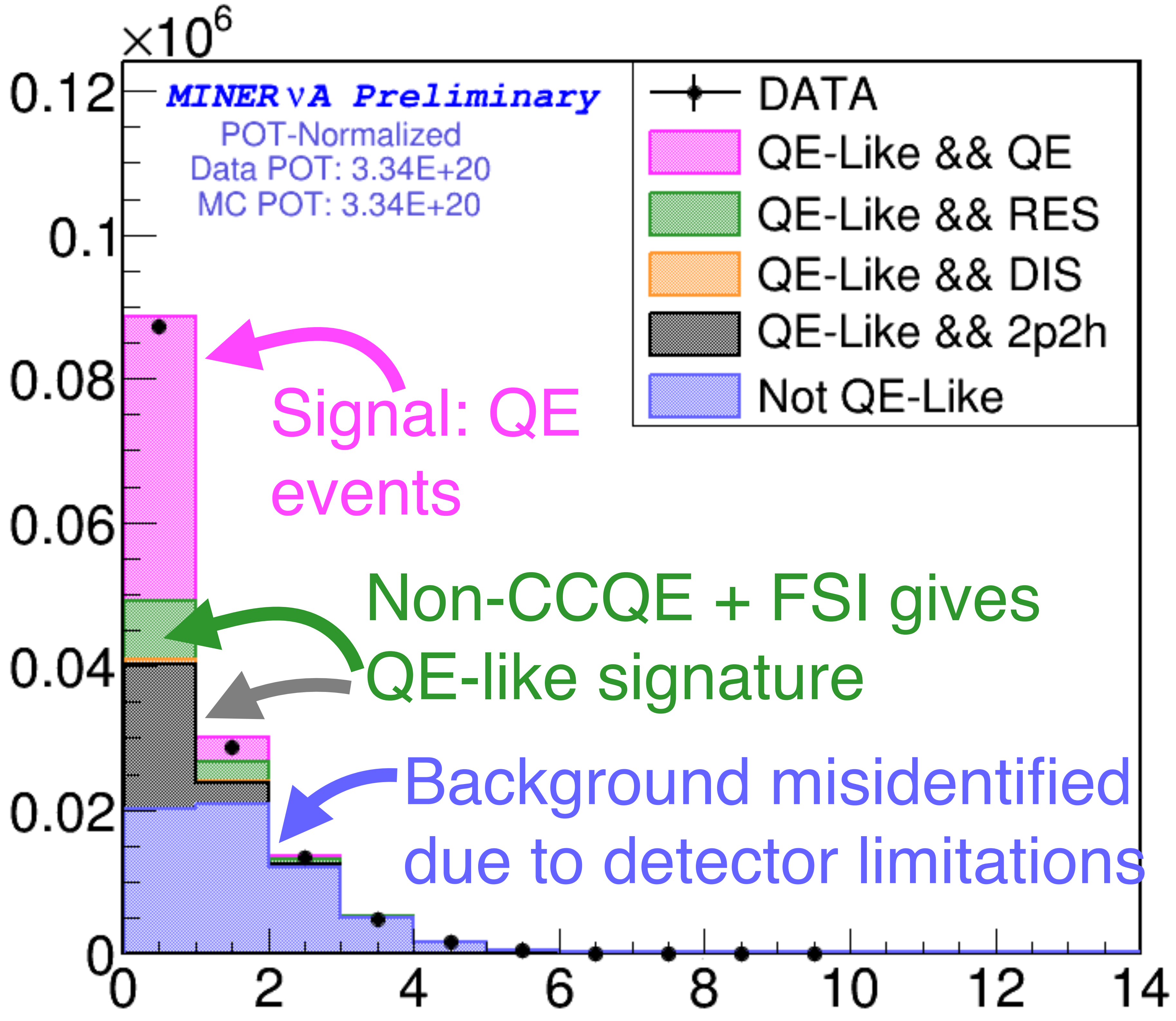


ν_μ QE	No FSI
ν_μ resonant	π absorption
$\bar{\nu}_\mu$ resonant	π absorption
$\bar{\nu}_\mu$ QE	Charge ex.

Summary - consequences of FSI

- FSI “fakers” make it hard to identify a sample of events corresponding to a single interaction mode (**exclusive sample**).
- This is particularly hard if your **detector** gives limited information (no muon/pion charges, poor low-energy detection etc)
- When we **compare data with models**, it’s hard to identify the effect of a single model (e.g. QE model) on the total spectrum

MINERvA’s CCQE-like selection



Signal: QE events

Non-CCQE + FSI gives QE-like signature

Background misidentified due to detector limitations

Summary - consequences of FSI

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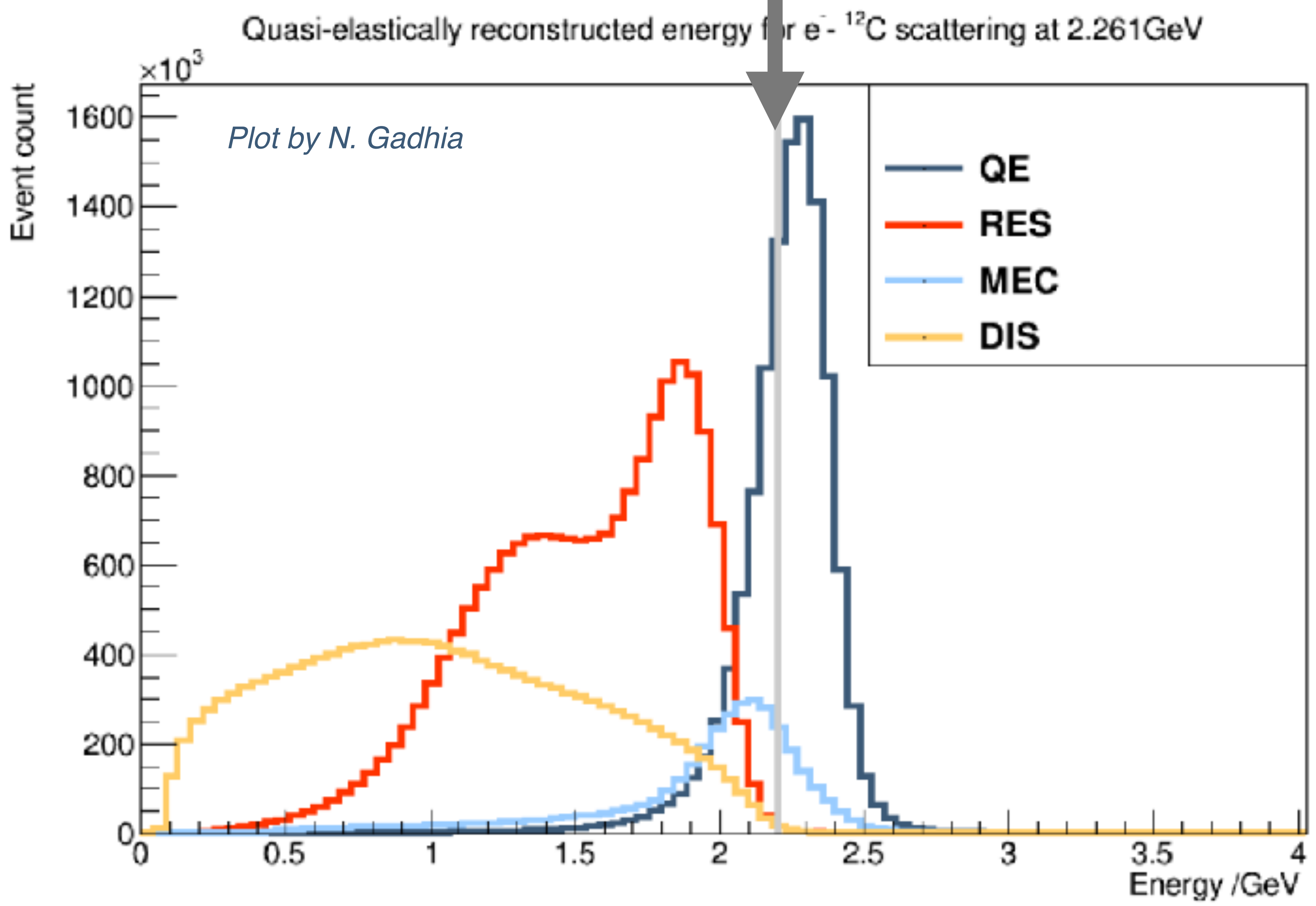
- This is particularly hard if your **detector** gives limited information (no muon/pion charges, poor low-energy detection etc)
- When we **compare data with models**, it’s hard to identify the effect of a single model (e.g. QE model) on the total spectrum
- Using the model for the wrong interaction mode will yield a **wrong neutrino energy**

True electron energy



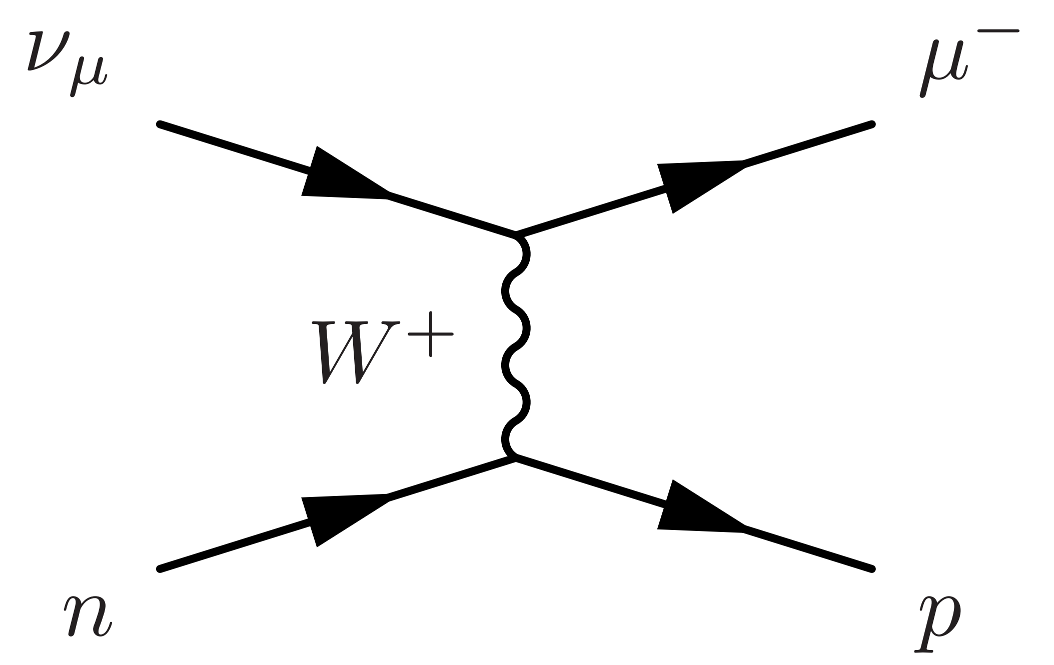
Mono-energetic electron scattering simulation

Energy reconstructed with the quasi-elastic formula for QE, resonant, DIS, and MEC events

Summary - consequences of FSI

- FSI “fakers” make it hard to identify a sample of events corresponding to a single interaction mode (**exclusive sample**).
- This is particularly hard if your **detector** gives limited information (no muon/pion charges, poor low-energy detection etc)
- When we **compare data with models**, it’s hard to identify the effect of a single model (e.g. QE model) on the total spectrum
- Using the model for the wrong interaction mode will yield a **wrong neutrino energy**
- Some FSI can knock out extra nucleons, alter interaction kinematics etc.
- We have some tricks to try and separate out these nuclear effects…

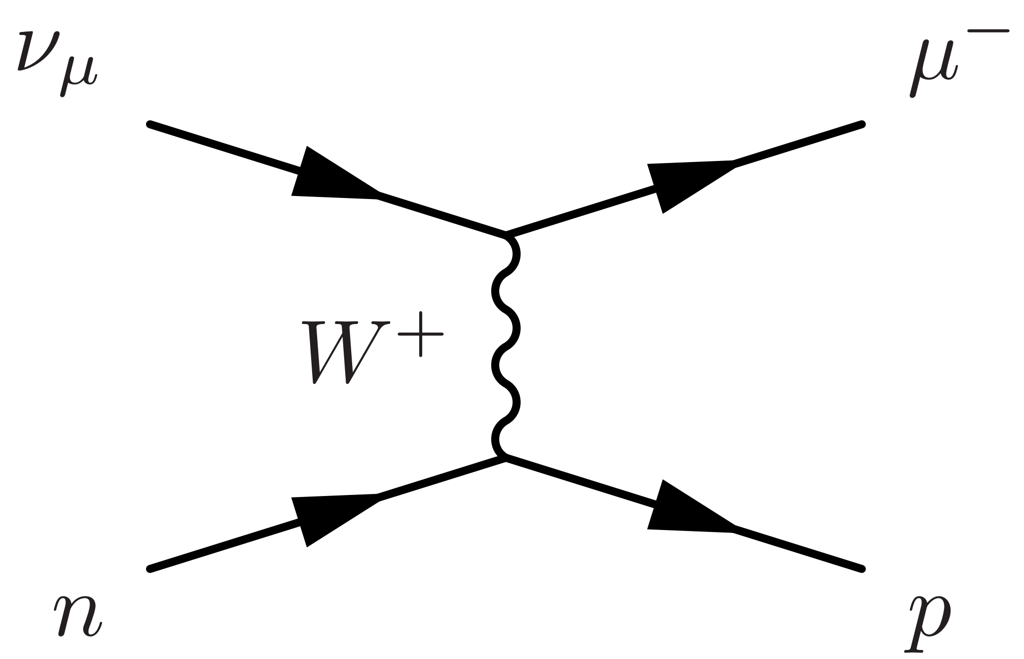
A trick for studying nuclear effects: transverse kinematics



Quasi-elastic ν_μ scattering from a **stationary** neutron

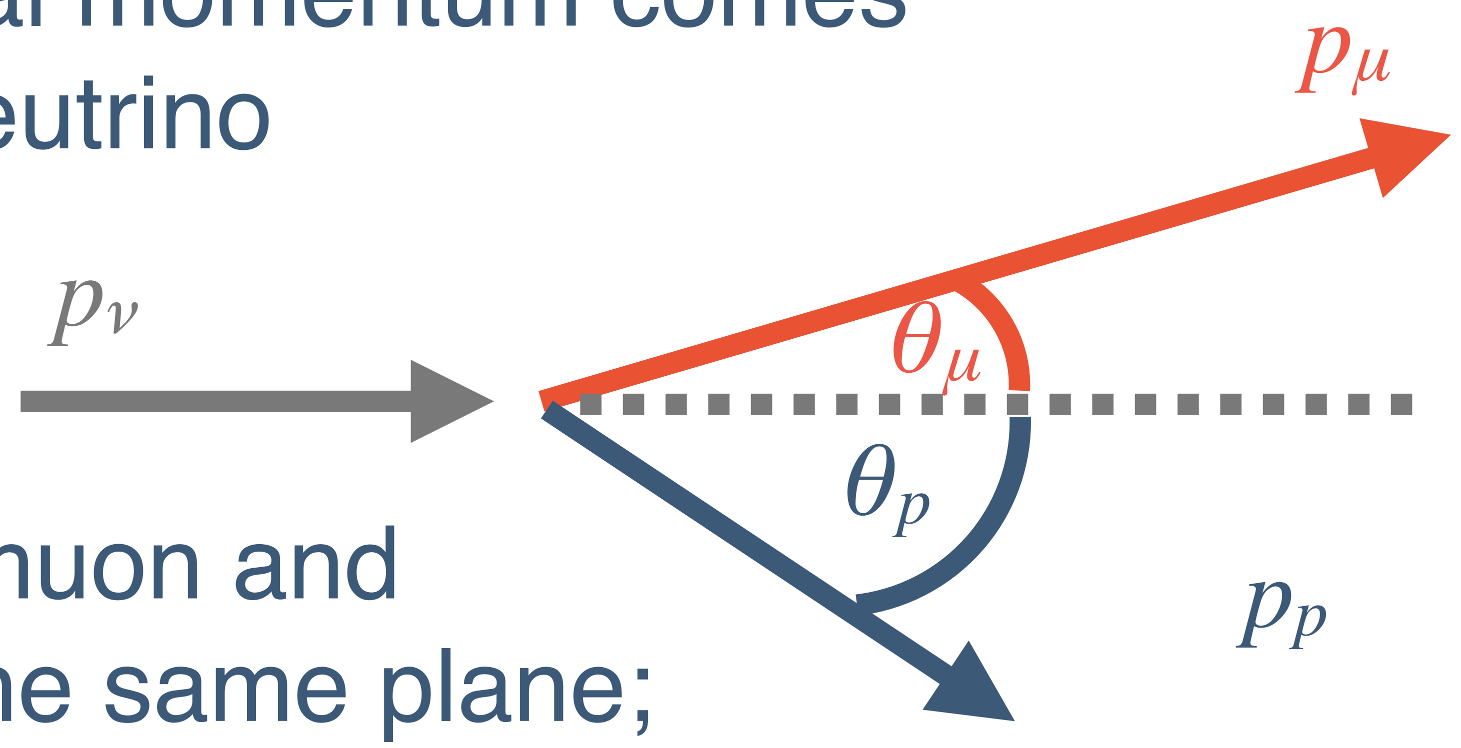
Phys.Rev. C94 (2016) no.1, 015503

A trick for studying nuclear effects: transverse kinematics



Quasi-elastic ν_μ scattering from a **stationary** neutron

All the initial momentum comes from the neutrino



Neutrino, muon and proton in the same plane;

$p_\mu \sin\theta_\mu = p_p \sin\theta_p$

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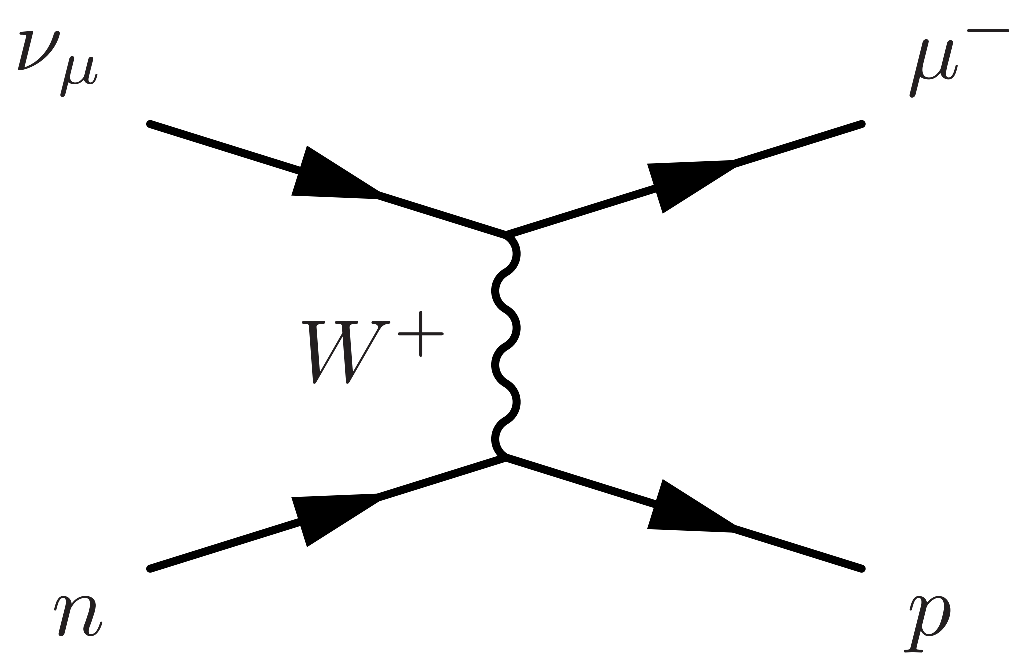
A trick for studying nuclear effects: transverse kinematics



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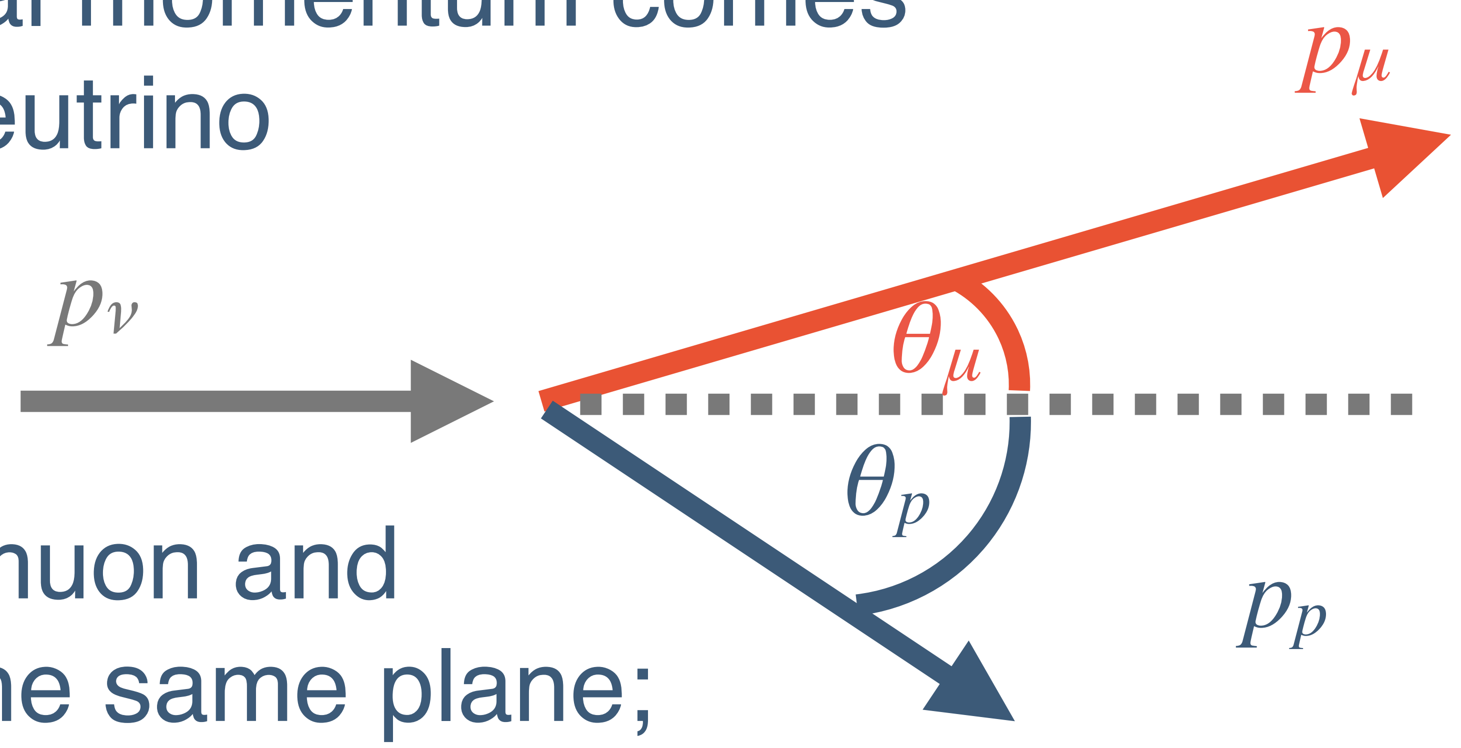
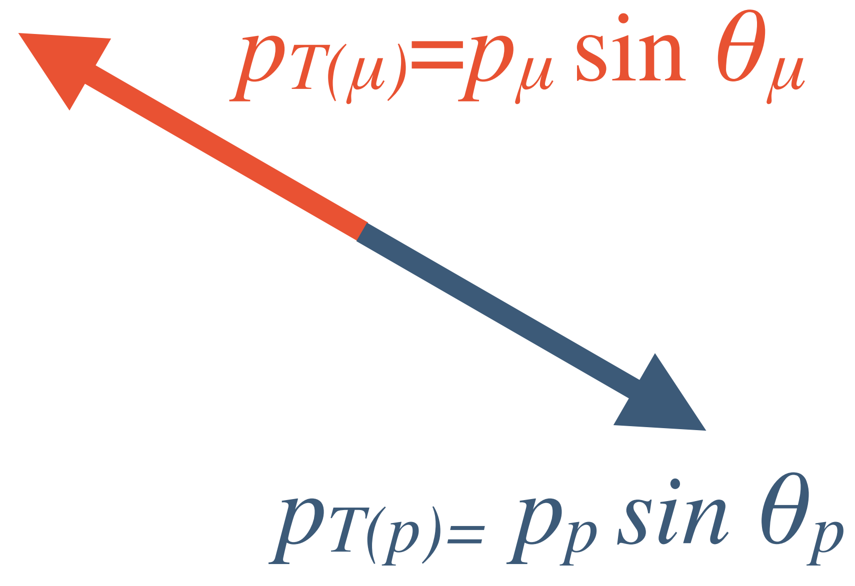


Neutrino, muon and proton in the same plane;

$p_\mu \sin\theta_\mu = p_p \sin\theta_p$

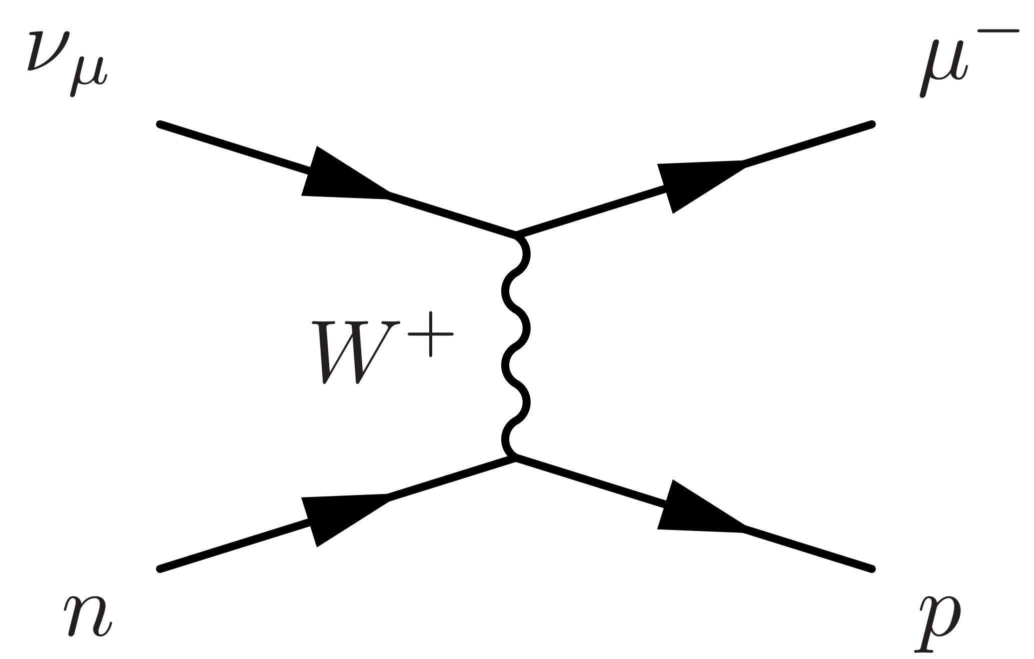
Project into a plane transverse to the beam;

$p_{T(\mu)}$ & $p_{T(p)}$ equal & opposite



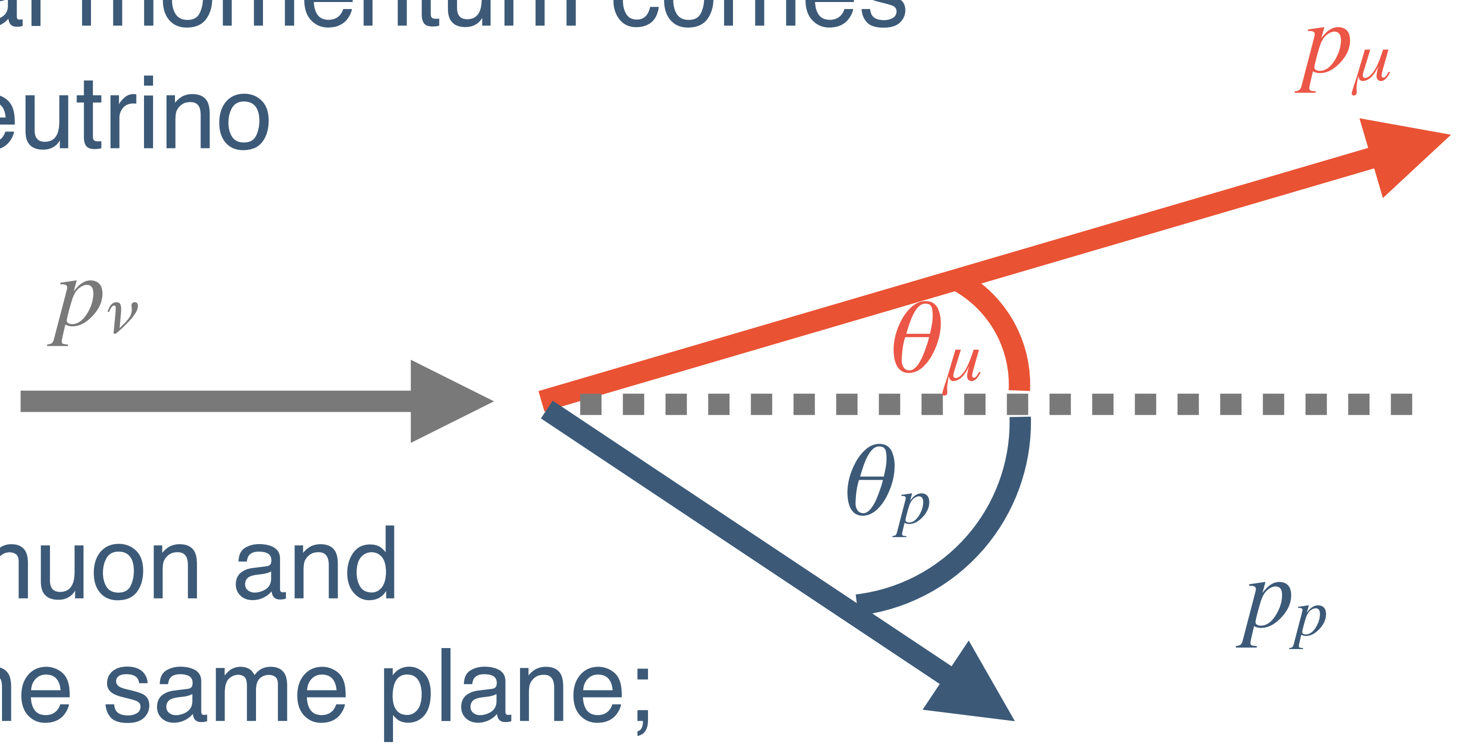
Phys.Rev. C94 (2016) no.1, 015503

A trick for studying nuclear effects: transverse kinematics



Quasi-elastic ν_μ scattering from a **stationary** neutron

All the initial momentum comes from the neutrino



Neutrino, muon and proton in the same plane;

$p_\mu \sin\theta_\mu = p_p \sin\theta_p$

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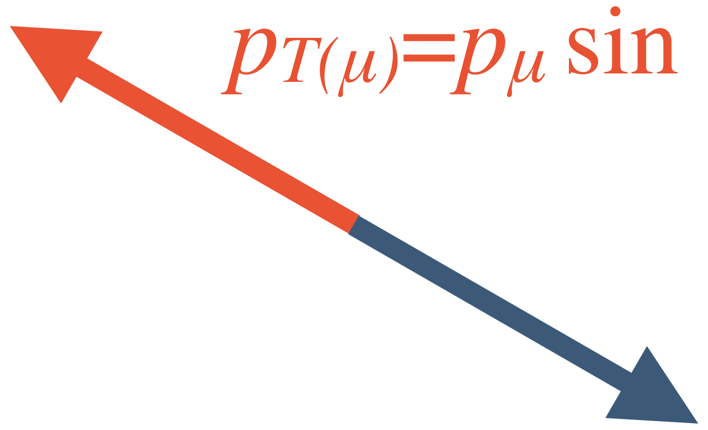

$p_{T(\mu)} = p_\mu \sin\theta_\mu$

$p_{T(p)} = p_p \sin\theta_p$

What if that doesn't happen?

Phys.Rev. C94 (2016) no.1, 015503

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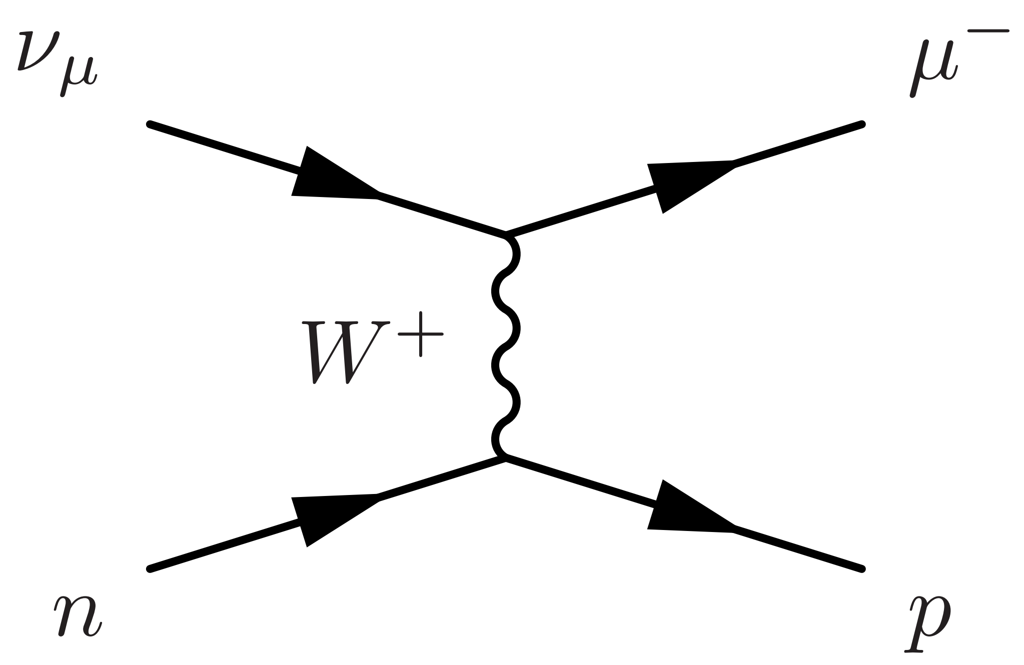

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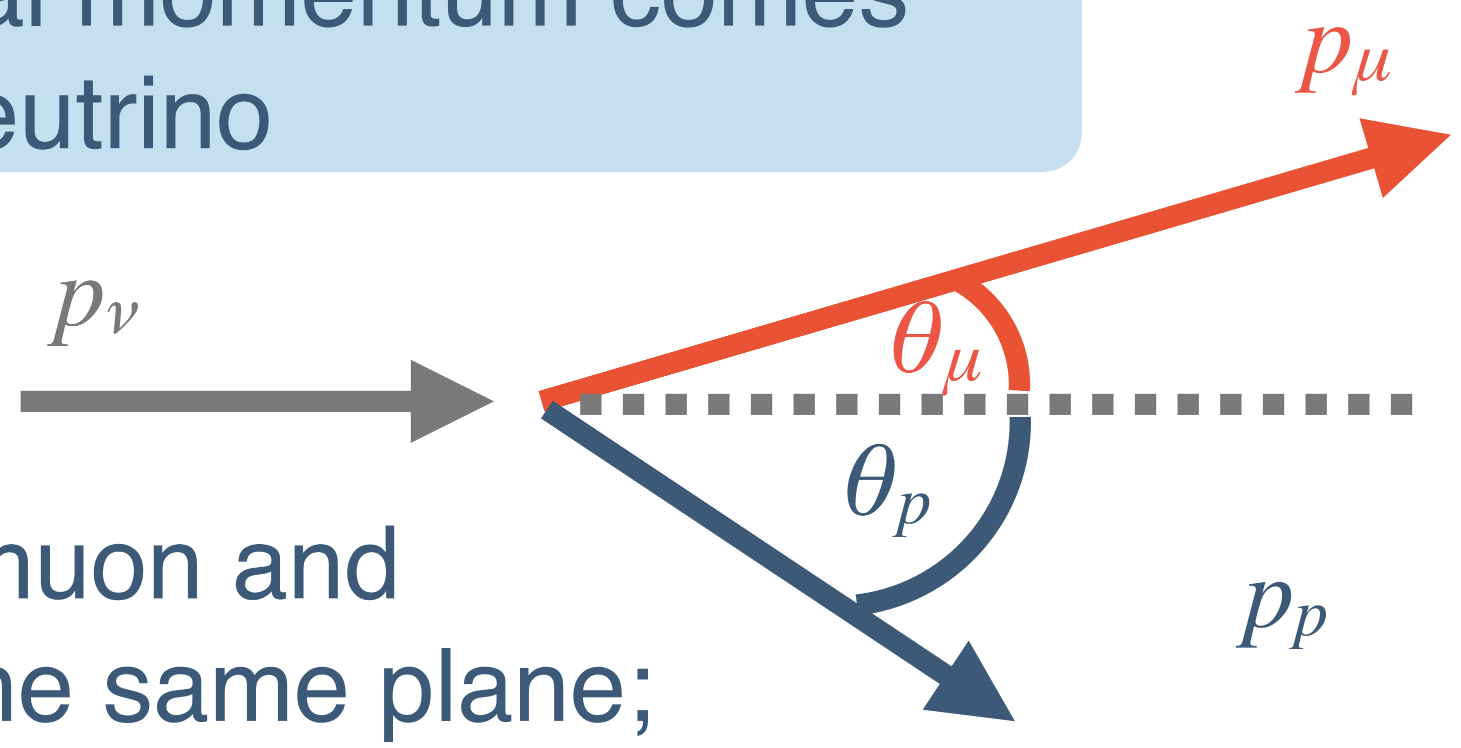

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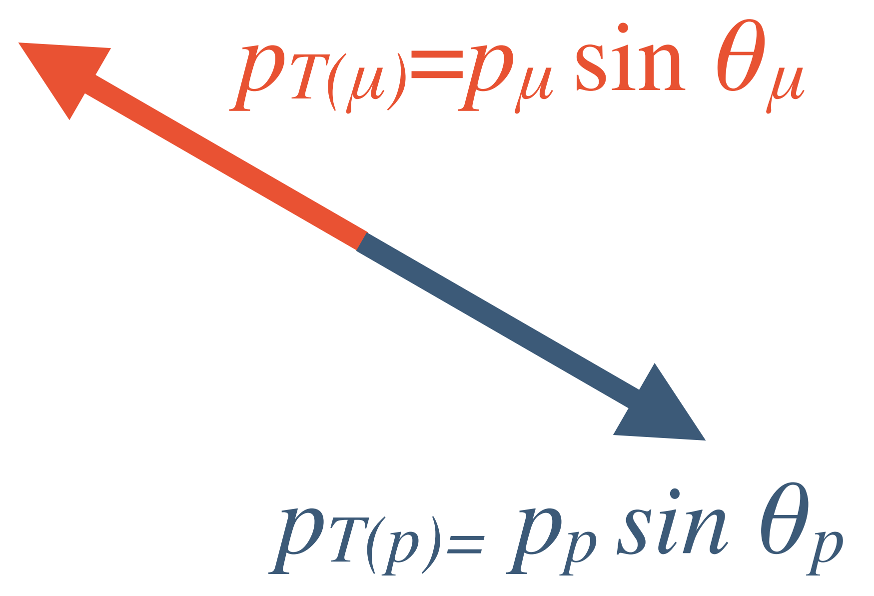
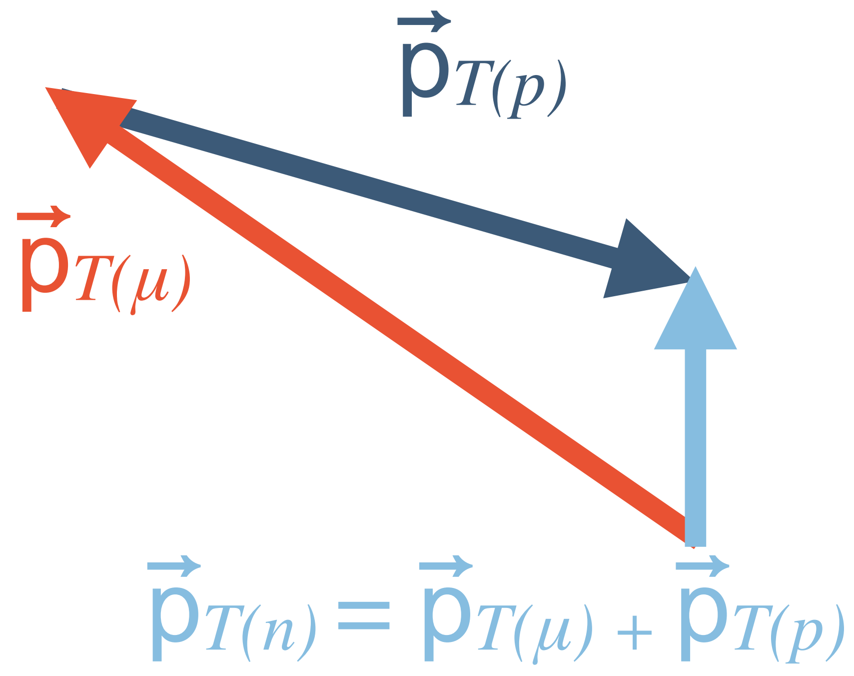


With nuclear effects, all this changes…



Any net momentum in the transverse plane must come from the **initial neutron**

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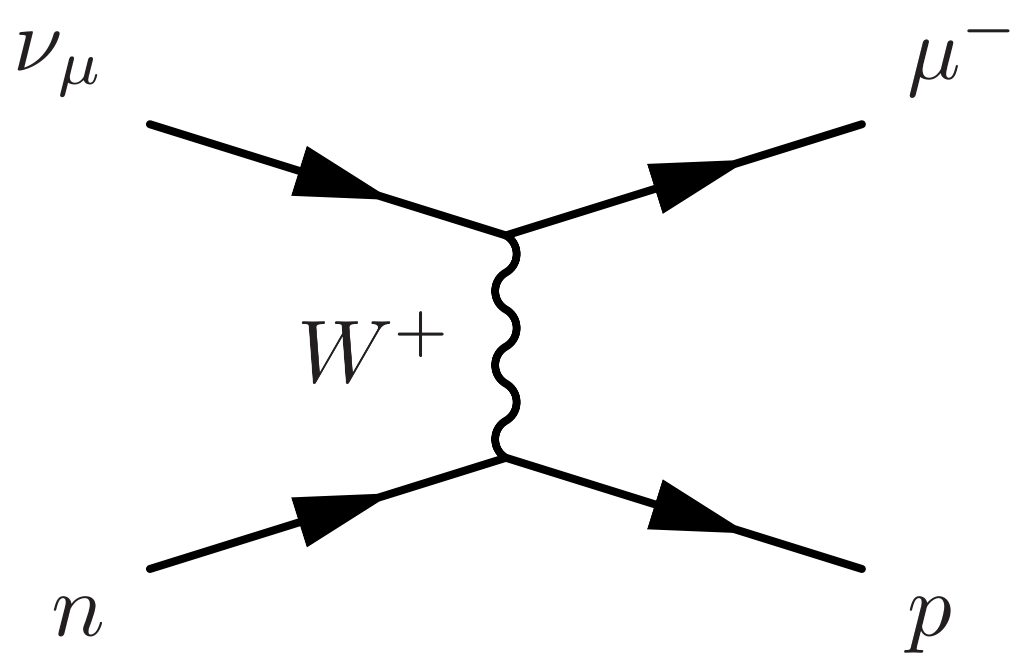

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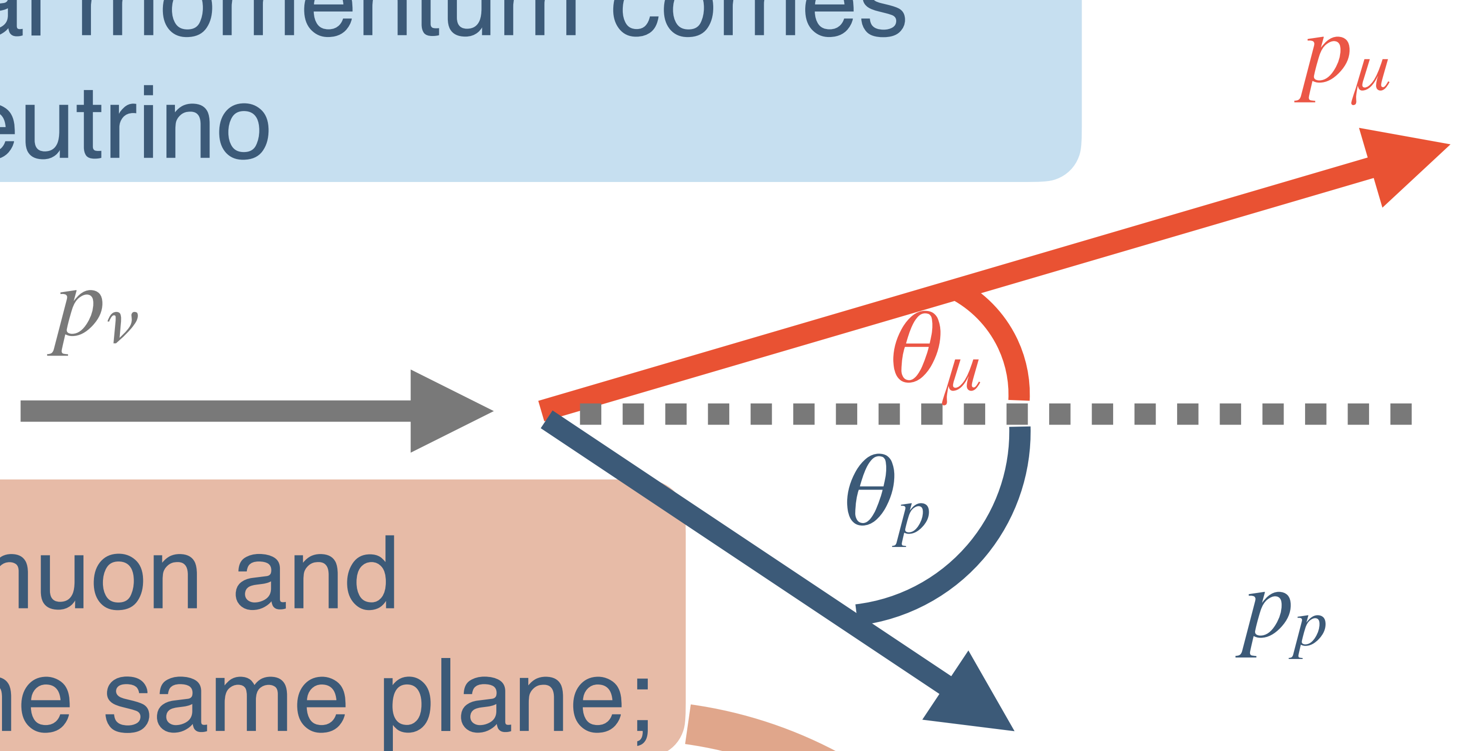

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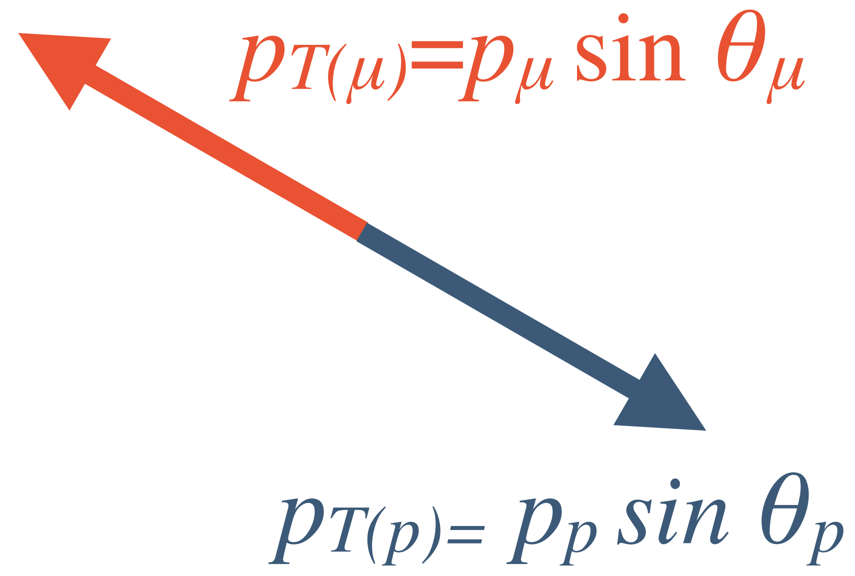

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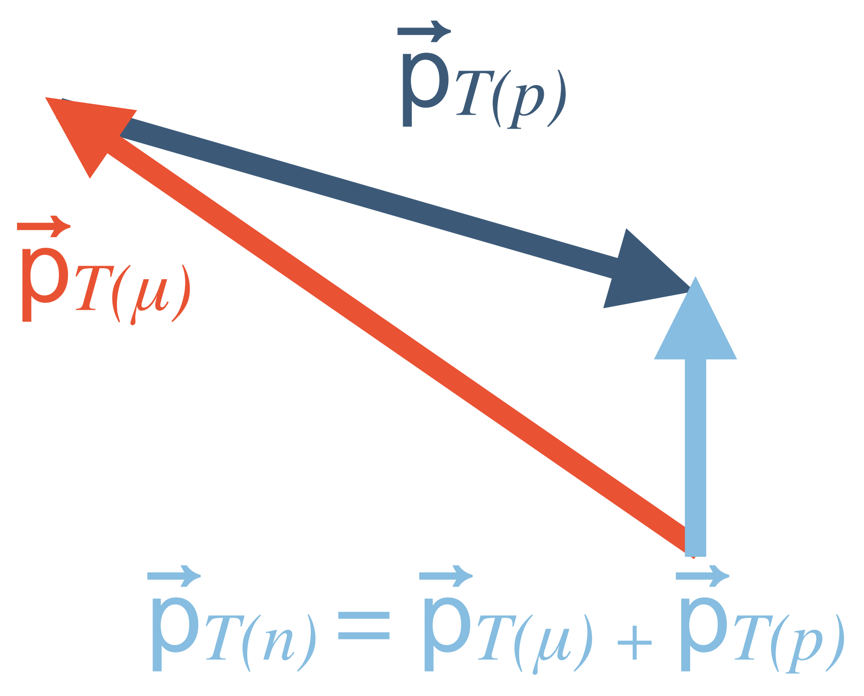
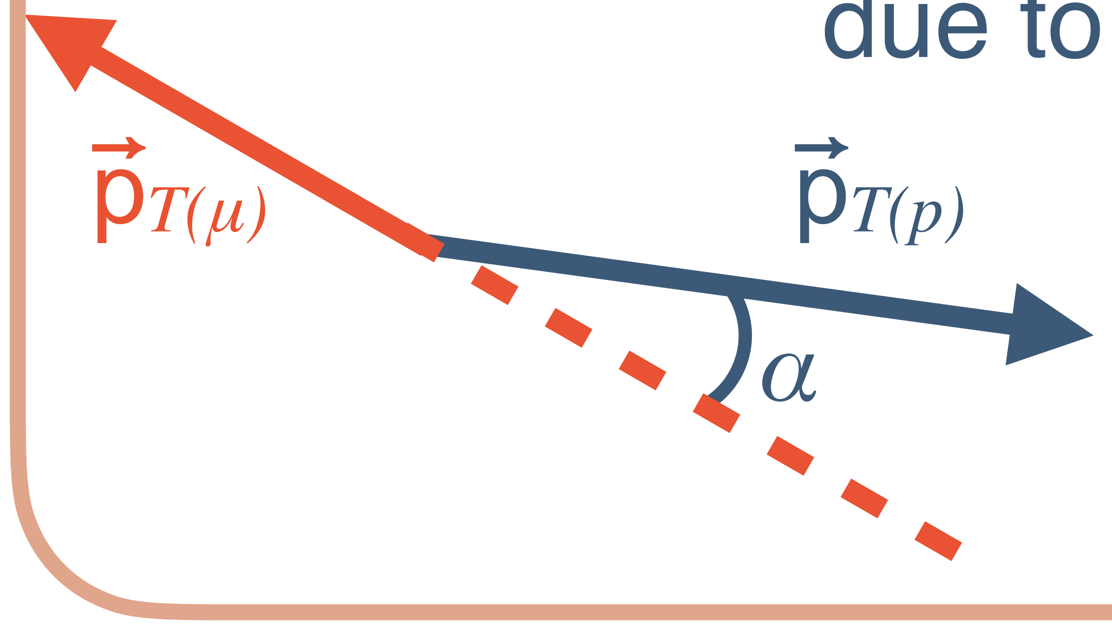


Any net momentum in the transverse plane must come from the **initial neutron**

If the proton moves out of the ν-μ plane, it must be due to **FSI**

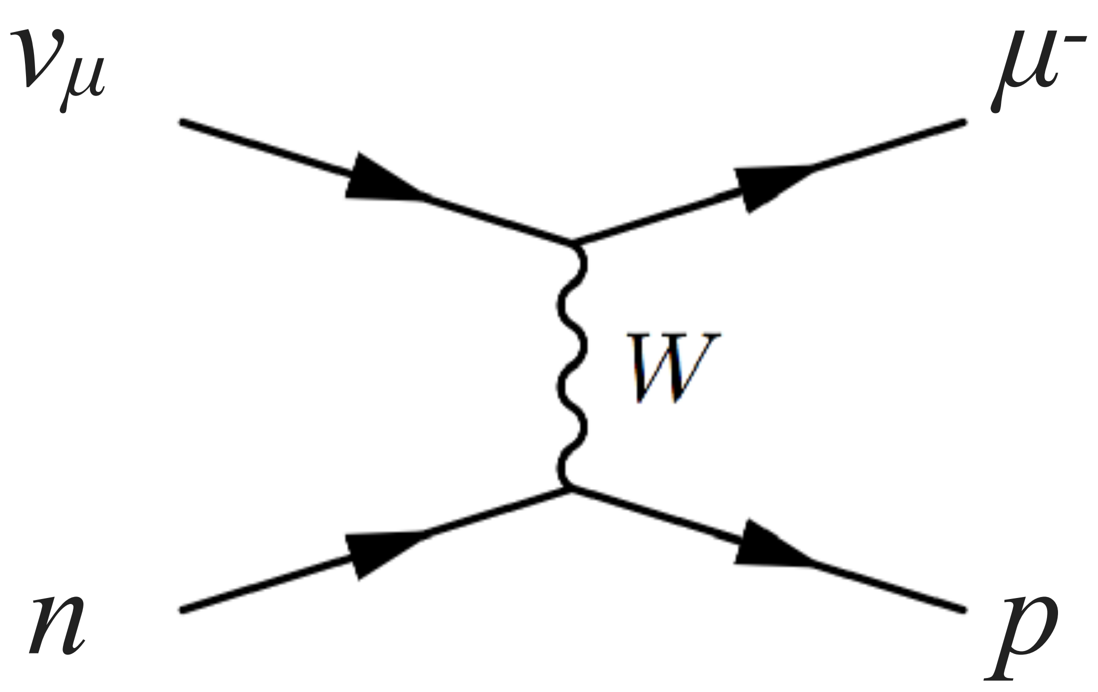


Studying variables like these can help us untangle the many factors affecting neutrino interactions

Phys.Rev. C94 (2016) no.1, 015503

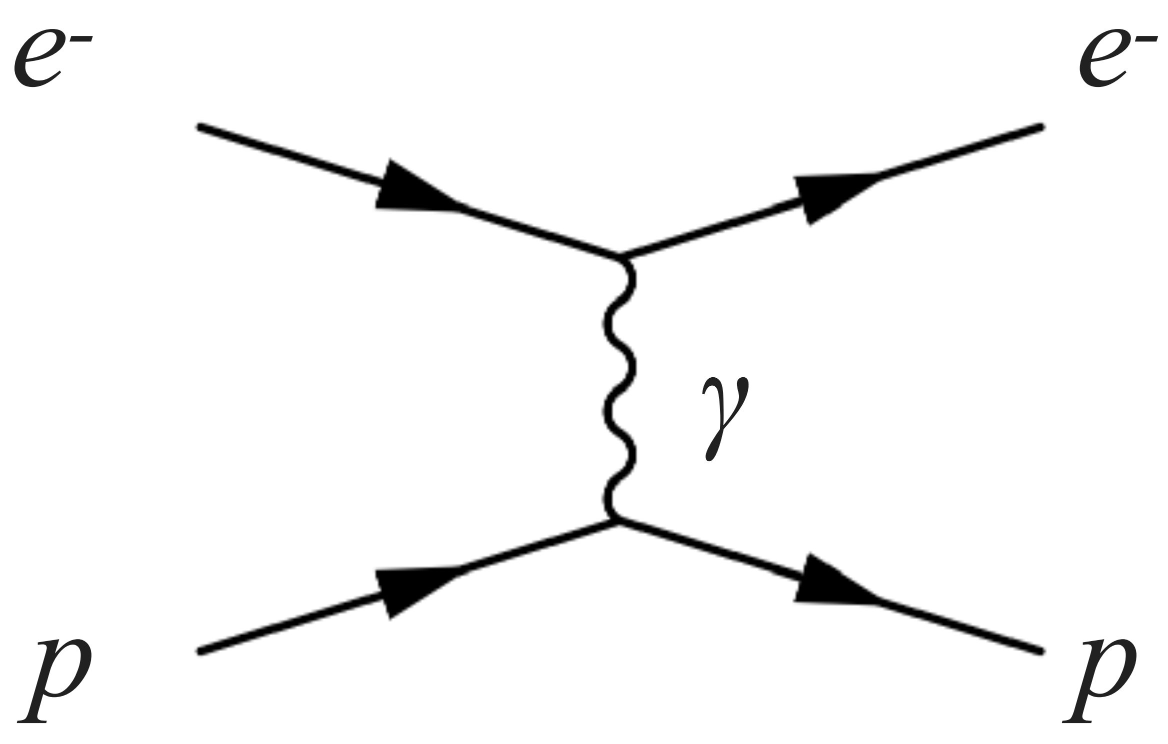
A little help from our friends - electrons!

Question 4



Neutrino scattering	Electron scattering

What's the same?
What's different?



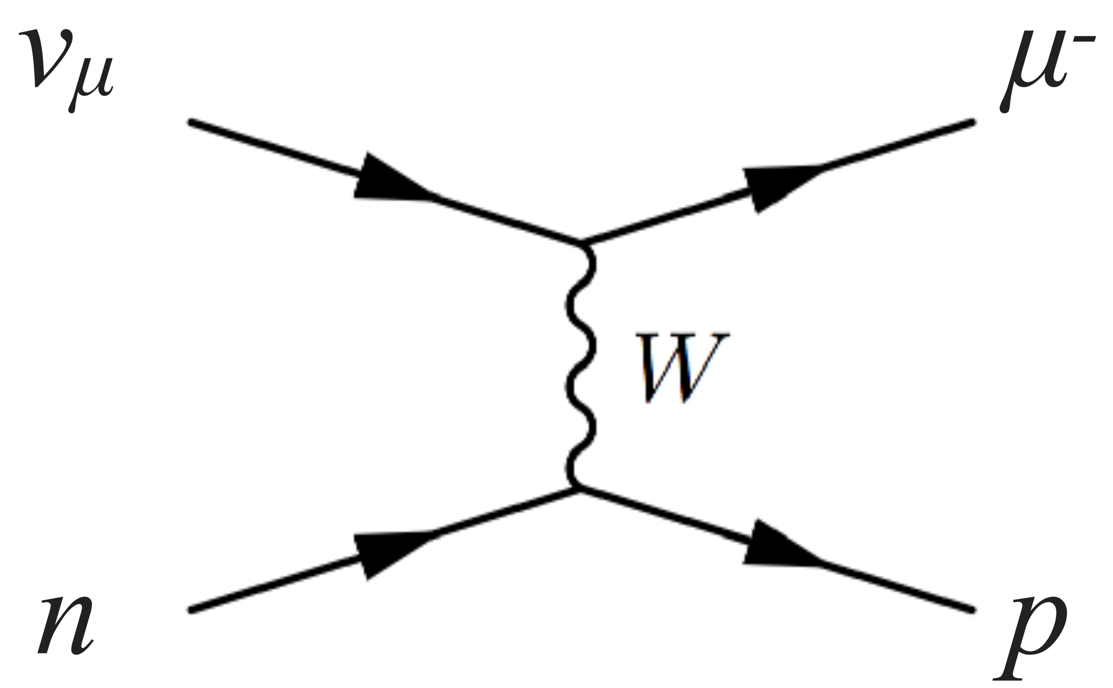
CEBAF Large Acceptance Spectrometer

MAINZER MIKROTRON

DEEP UNDERGROUND NEUTRINO EXPERIMENT

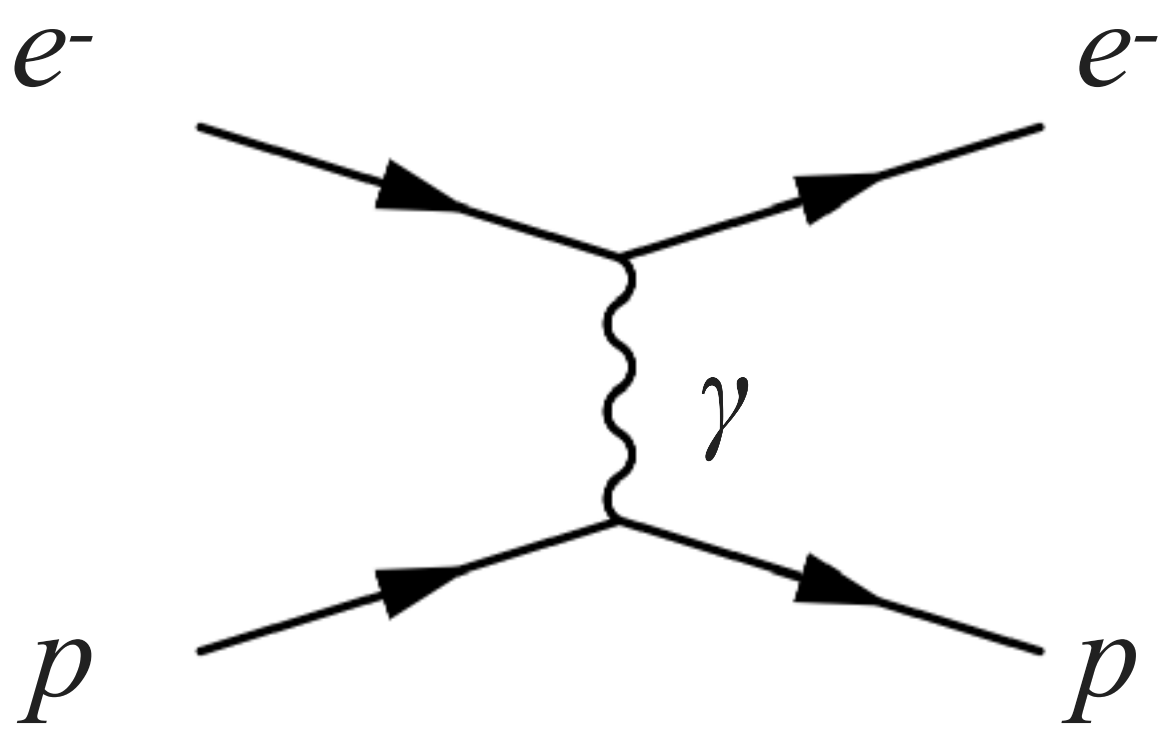
A little help from our friends - electrons!

Question 4



Neutrino scattering	Electron scattering
Small cross section	Large cross section
Broad-band beams	Mono-energetic beams
Vector+axial interaction	Vector interaction only

The same nuclear physics



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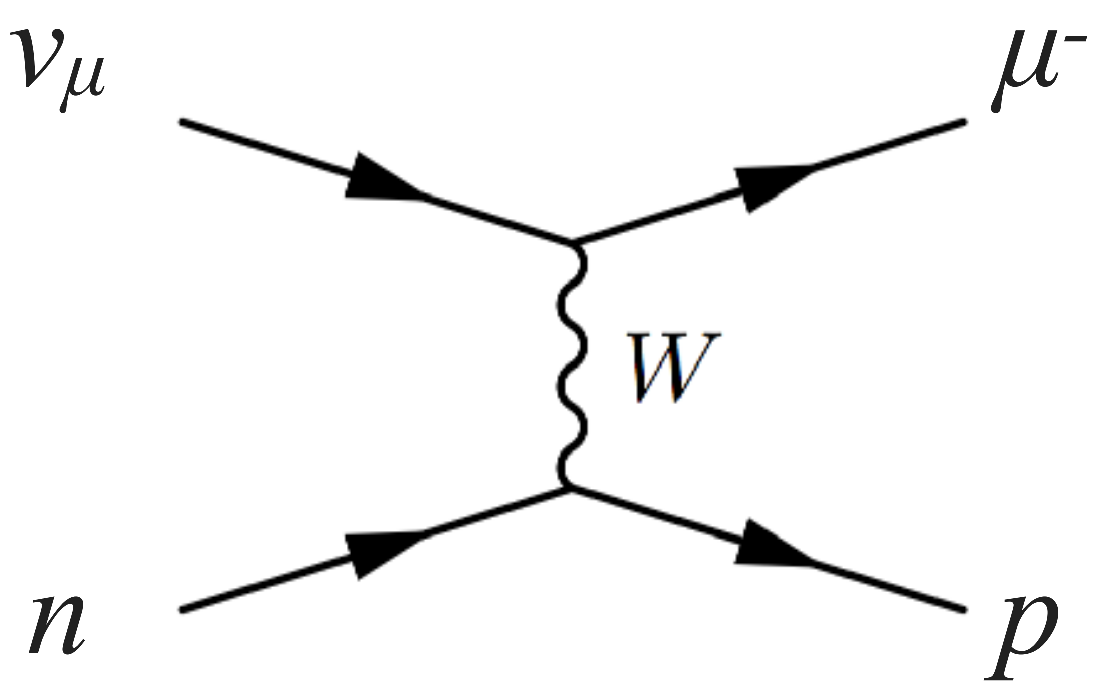

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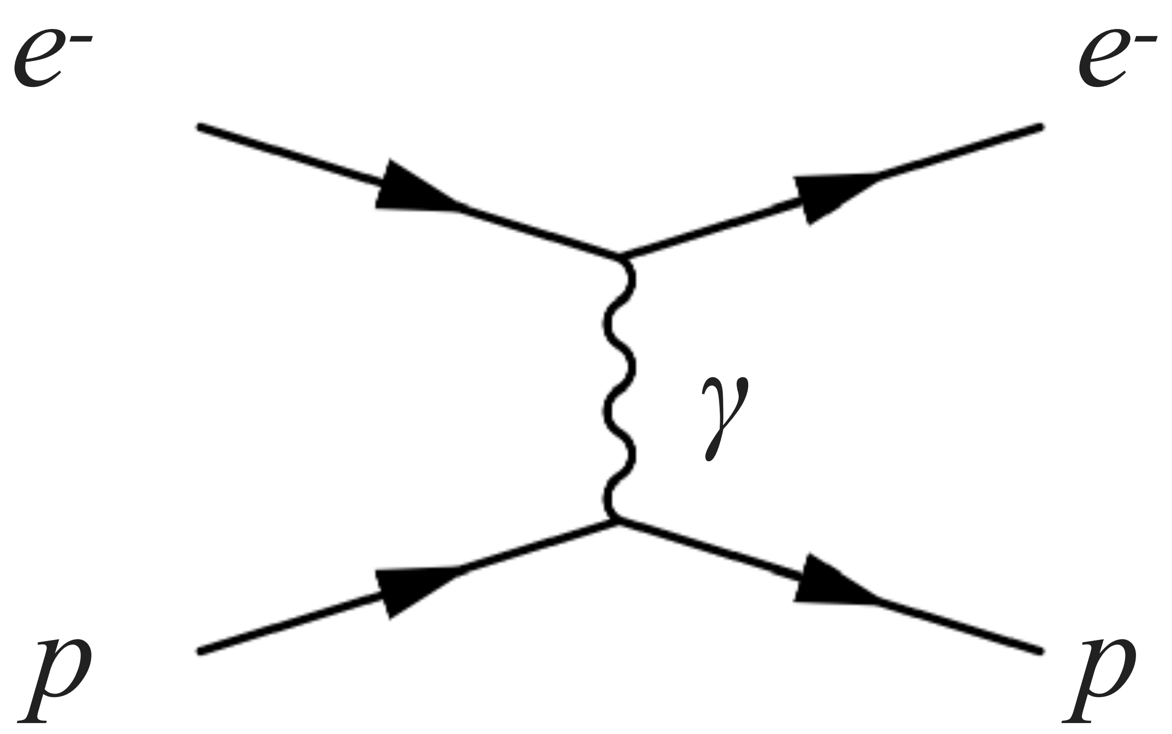
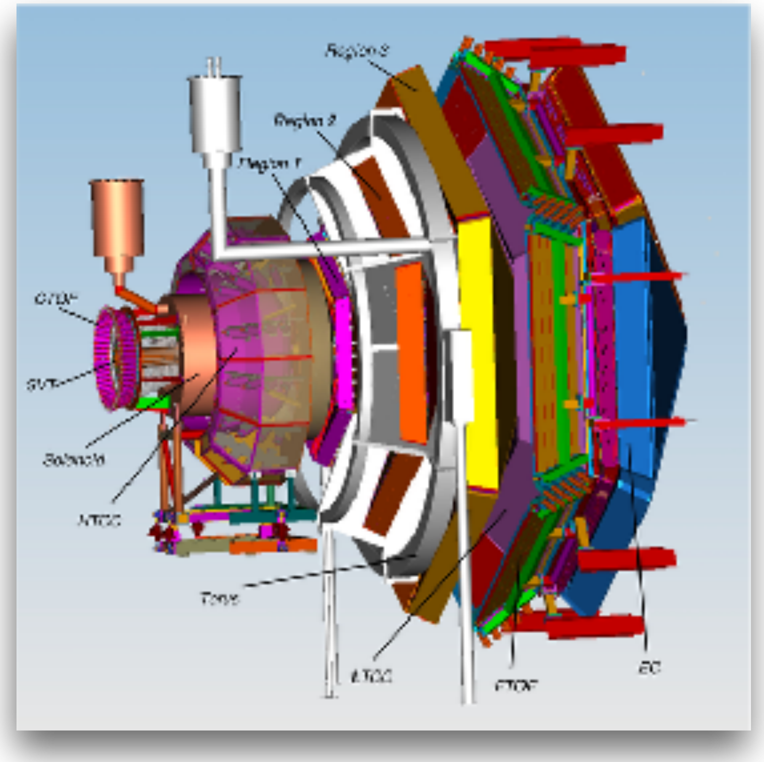


e4V



CLAS detector in JLab electron beam

+

Neutrino-interaction simulation modified for electrons

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

=

Vector part of models tested for

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

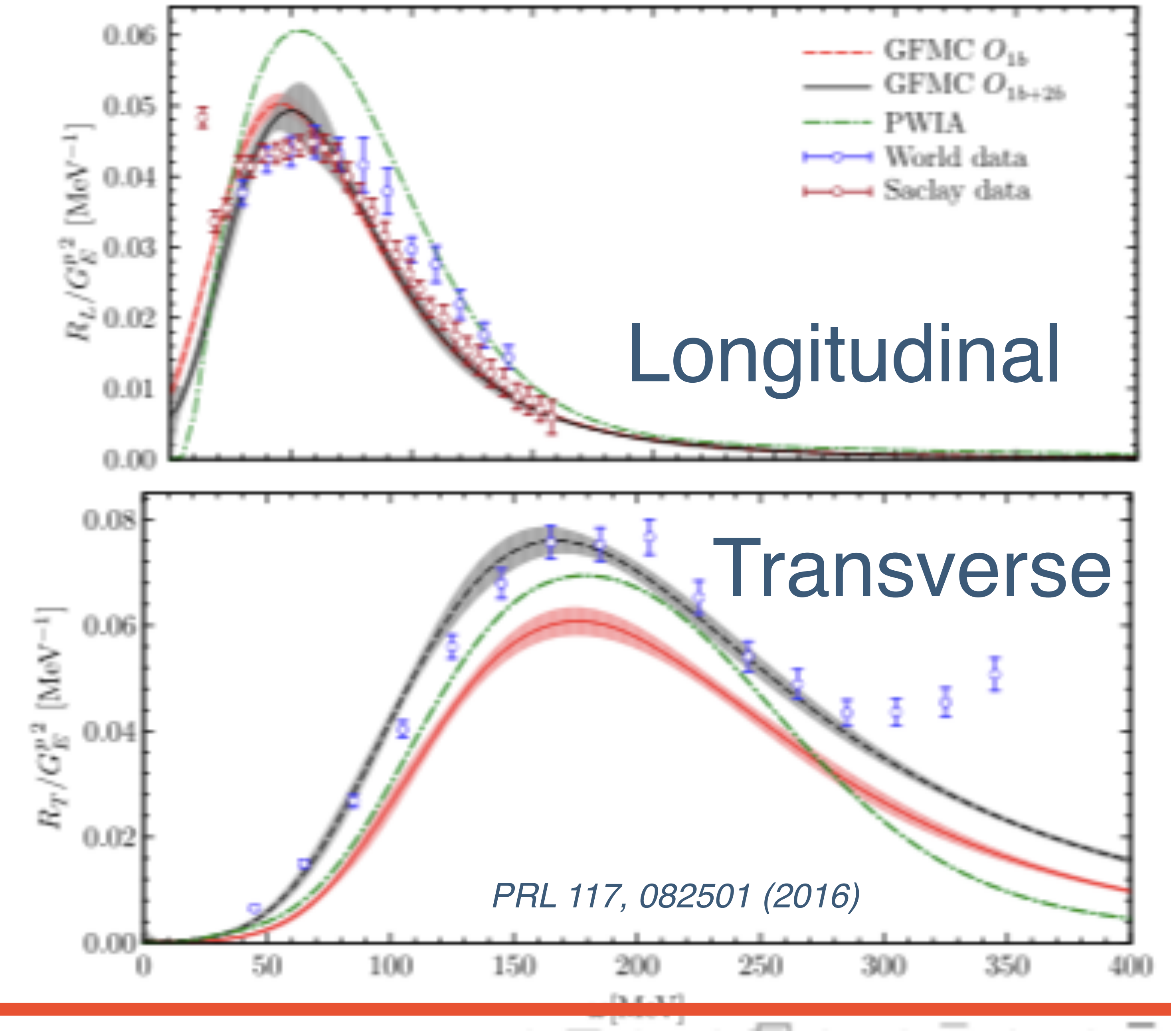
(the axial part's for us to test…)

Modeling nuclei

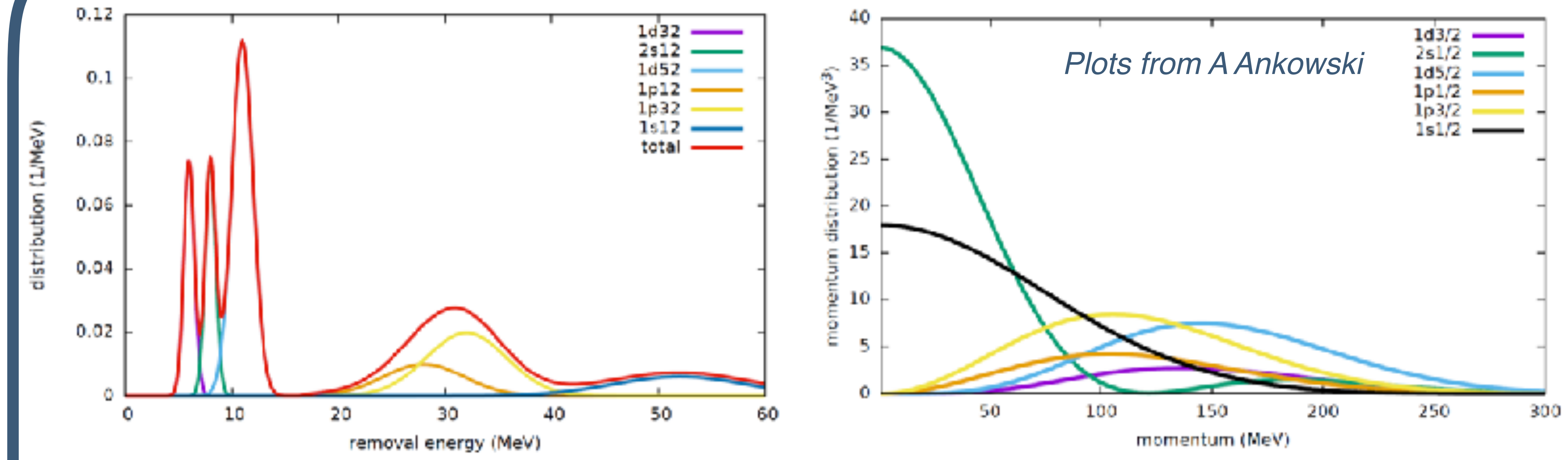
- *Ab initio* methods like spectral functions and Green's function Monte Carlo accurately model simple, symmetric nuclei in certain regimes

- Computational complexity limits them for heavier nuclei

Green's Function Monte Carlo



PRL 117, 082501 (2016)



Plots from A Ankowski

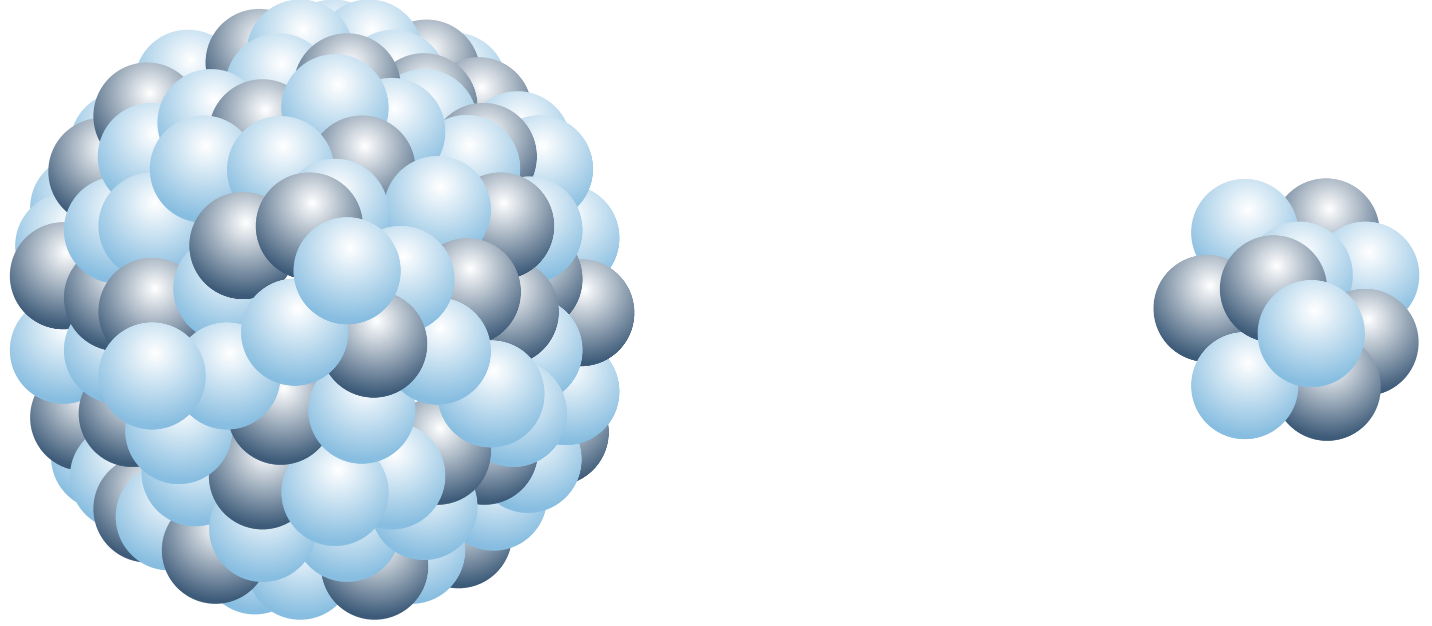
Spectral functions (removal energy and momentum) for nucleons ^{40}Ar

Modeling nuclei

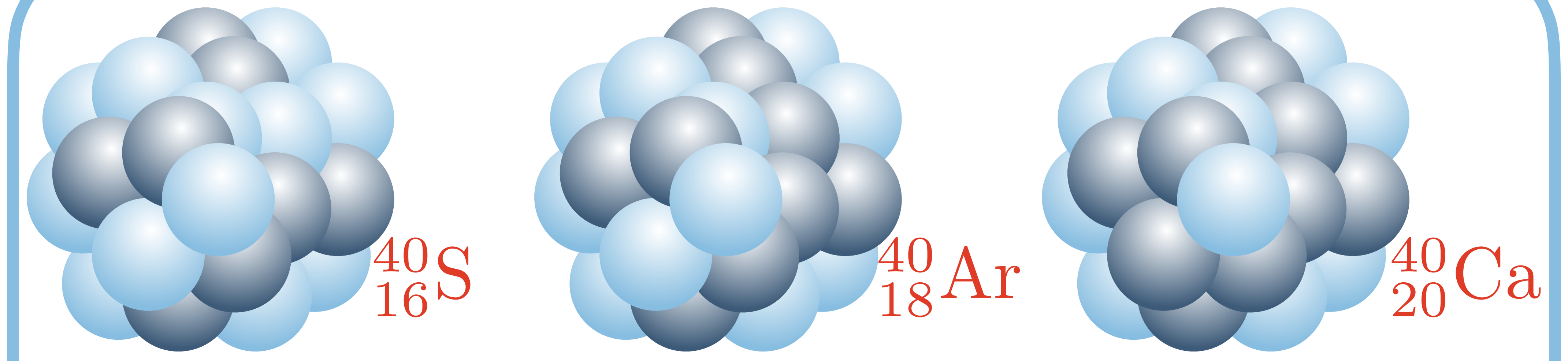
- *Ab initio* methods like spectral functions and Green's function Monte Carlo accurately model simple, symmetric nuclei in certain regimes

- Computational complexity limits them for heavier nuclei

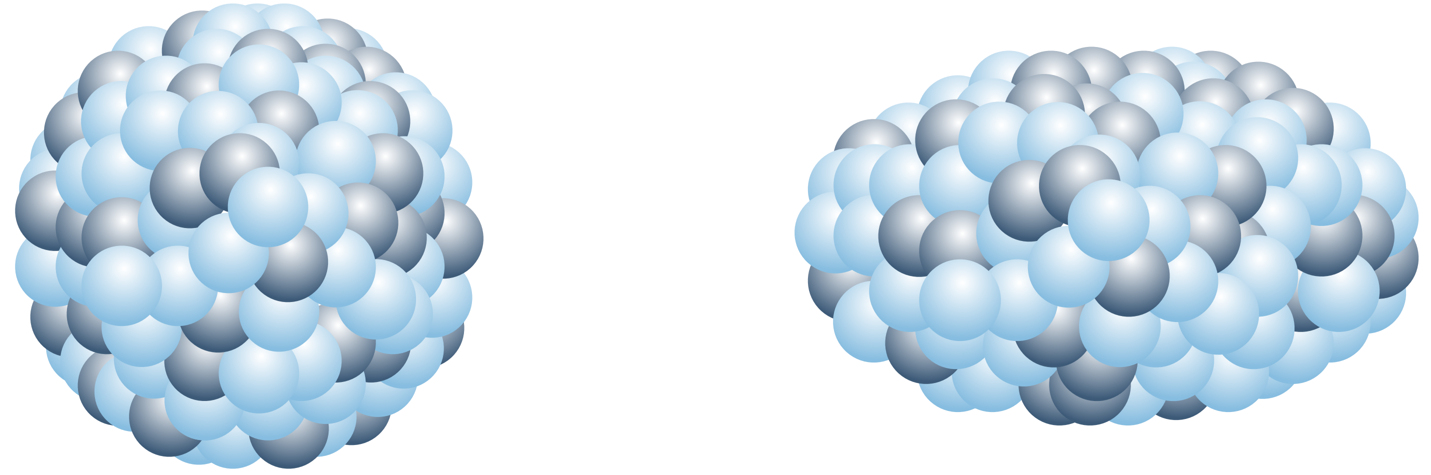
- Nuclear effects depend on many factors; it's hard to generalize models or measurements from one nucleus to another



Number of nucleons (atomic mass A)



Neutron-proton ratio (isobars)



Shapes, binding energies etc are consequences of a complex shell structure

Universality and scaling

The idea:

- find some **universal** property or function that is the **same for many nuclei**
- Make **predictions** for nuclei that haven't yet been studied

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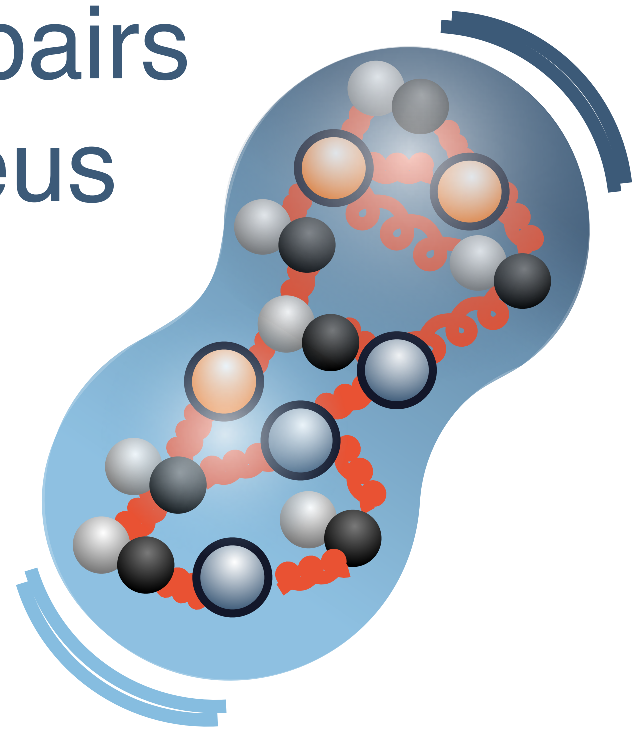

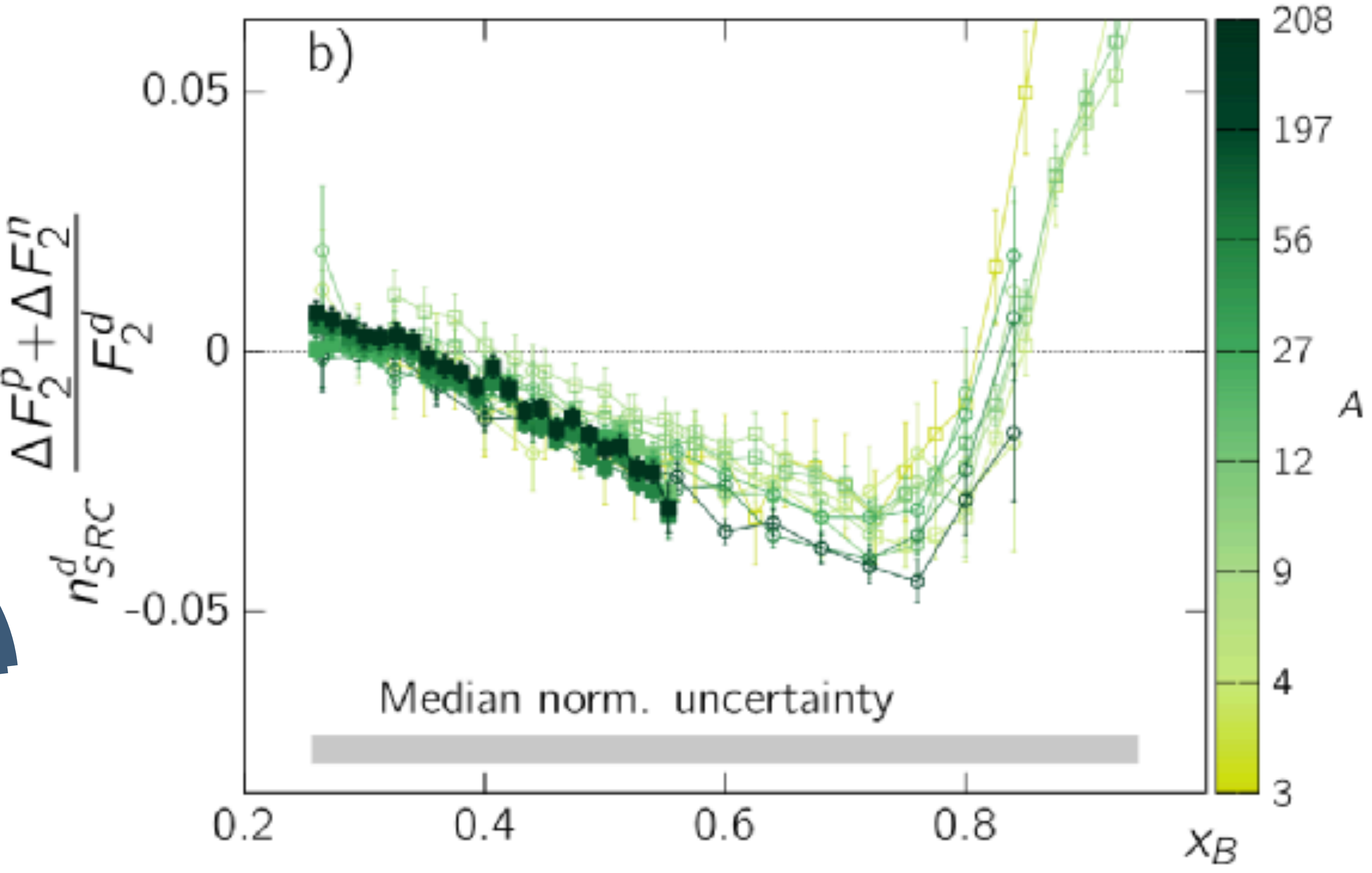

(Each colour represents a different element/isotope)

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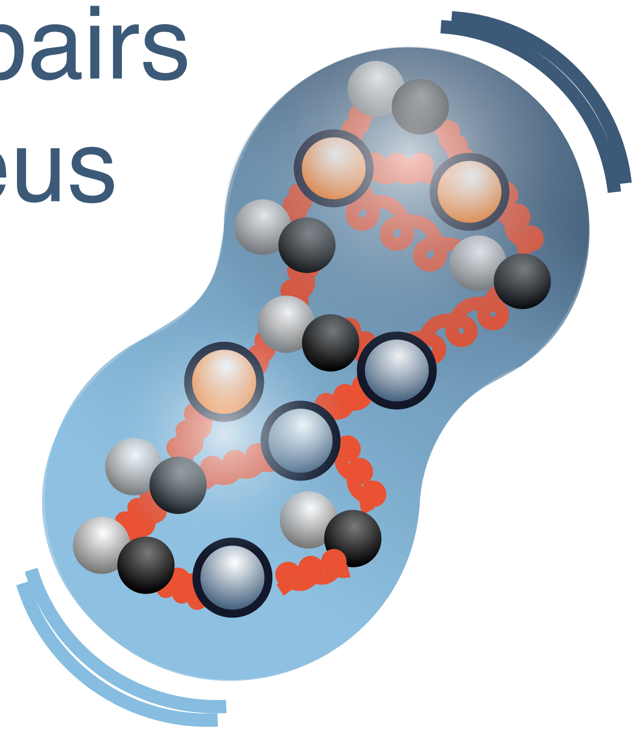

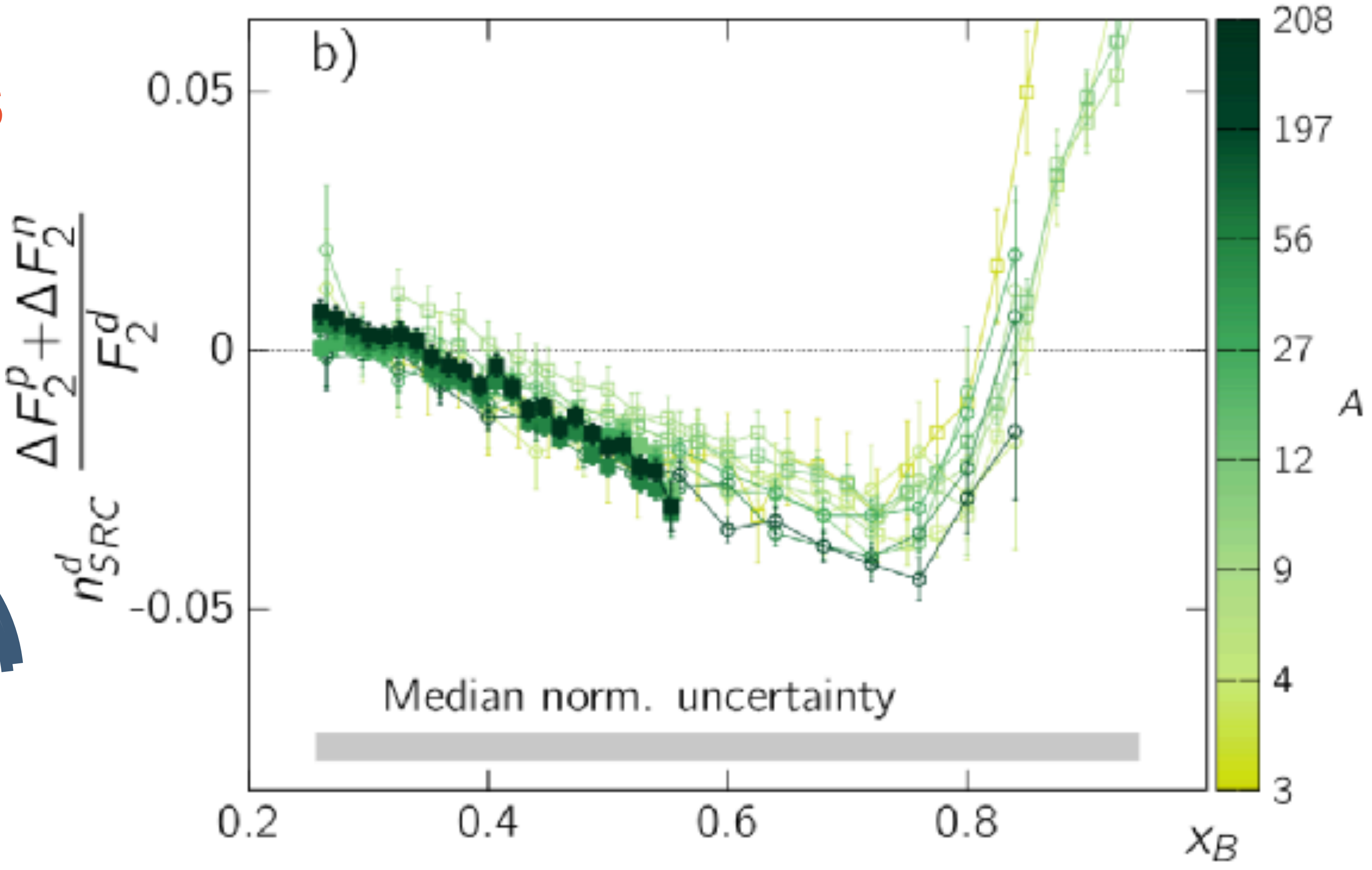

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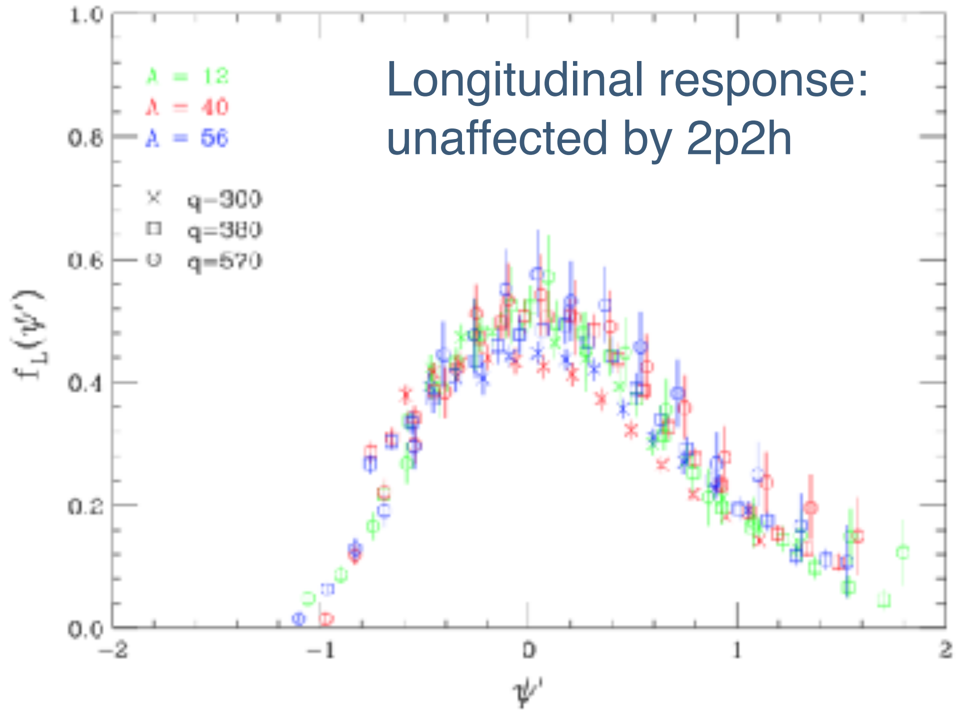
Super-scaling models seek a variable $\psi(q,w)$ such that

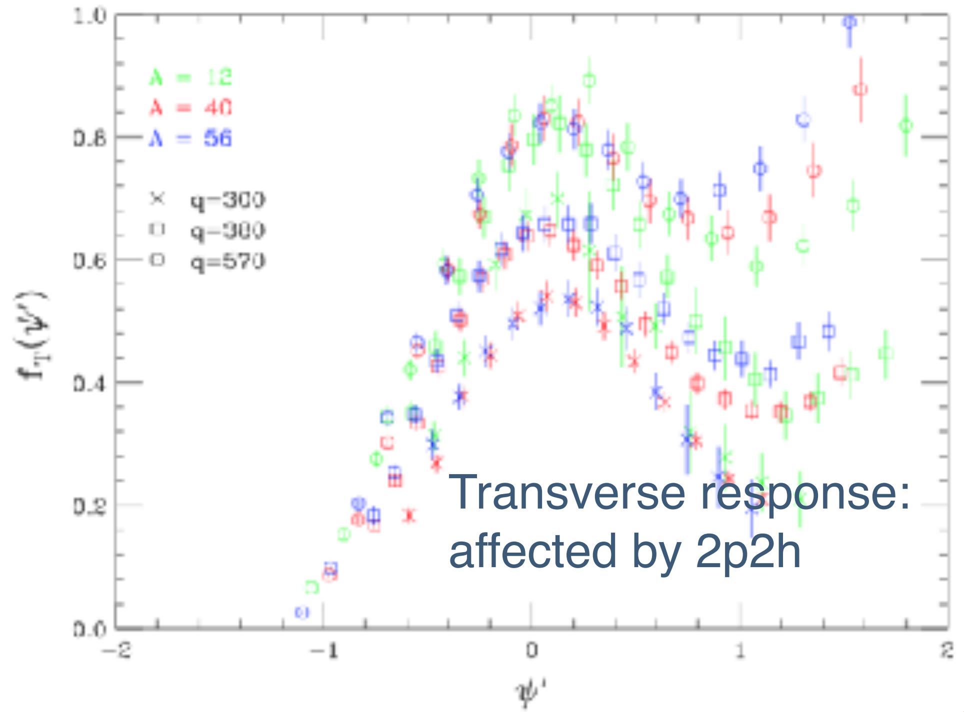
- cross section per nucleon is a function only of ψ
- …and is universal for all nuclei

These currently model electron scattering well in some regimes…



Longitudinal response: unaffected by 2p2h

…and less well in others



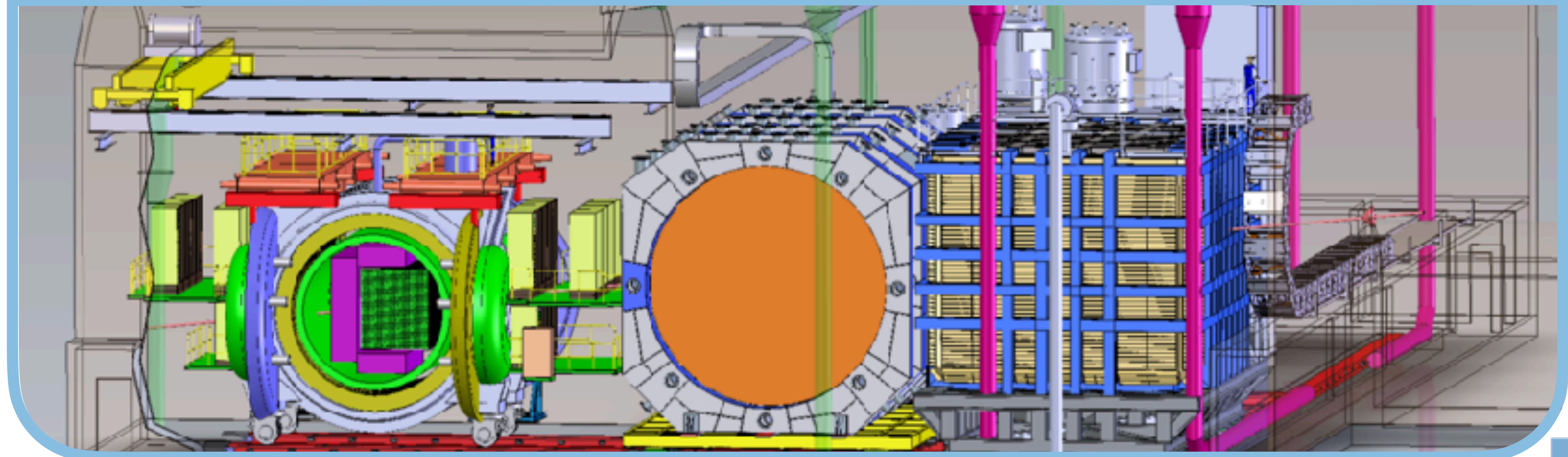
Transverse response: affected by 2p2h

Phys.Rev. C60 (1999) 065502

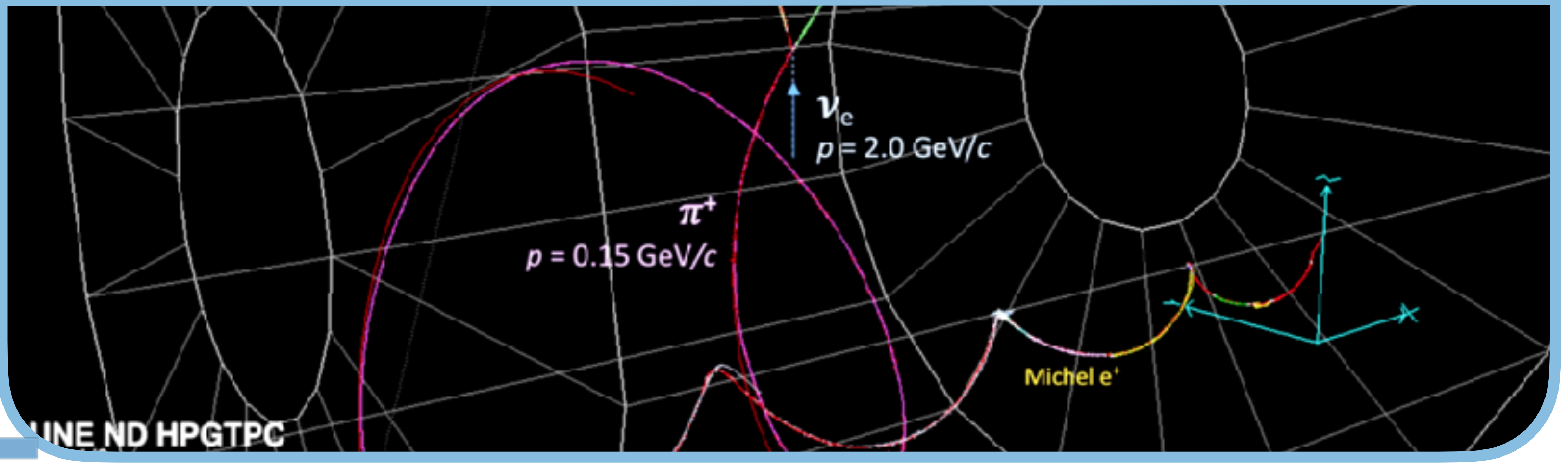
Next step - test models with neutrino data!

Neutrino interaction analysis with DUNE simulation

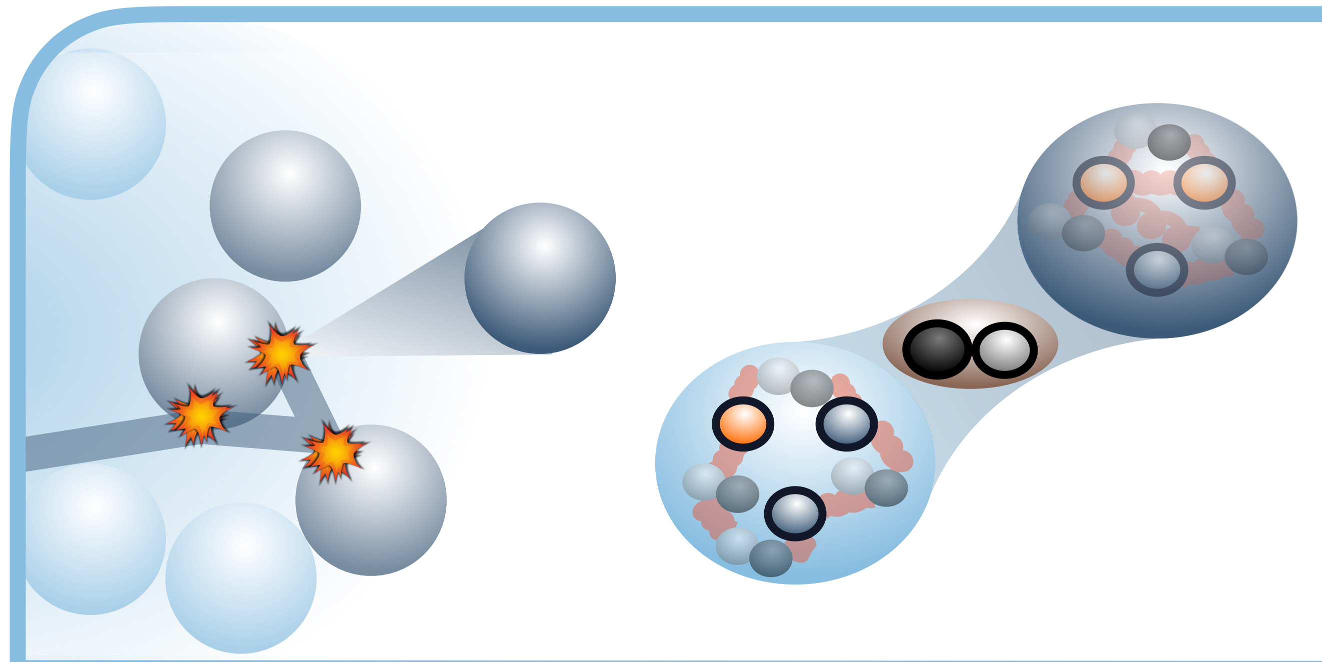
DUNE's near detectors will have unique capabilities (Learn more in the mini talks)

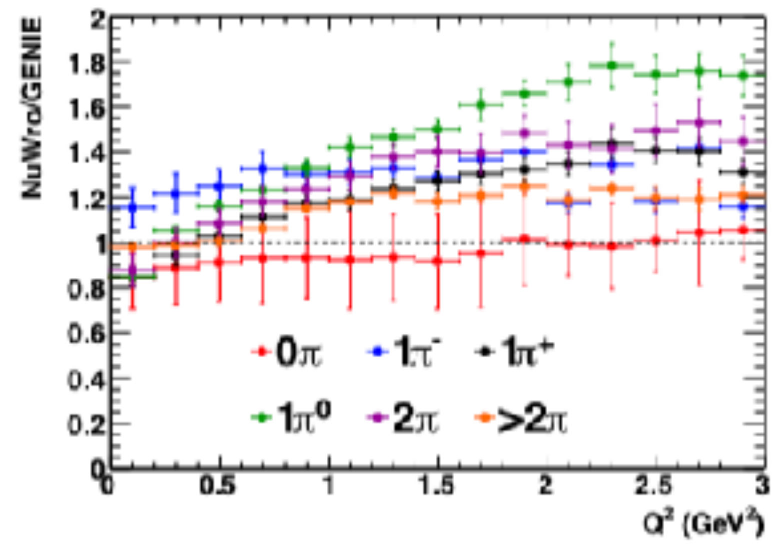


By analyzing simulation, we can understand how neutrino interactions will appear…



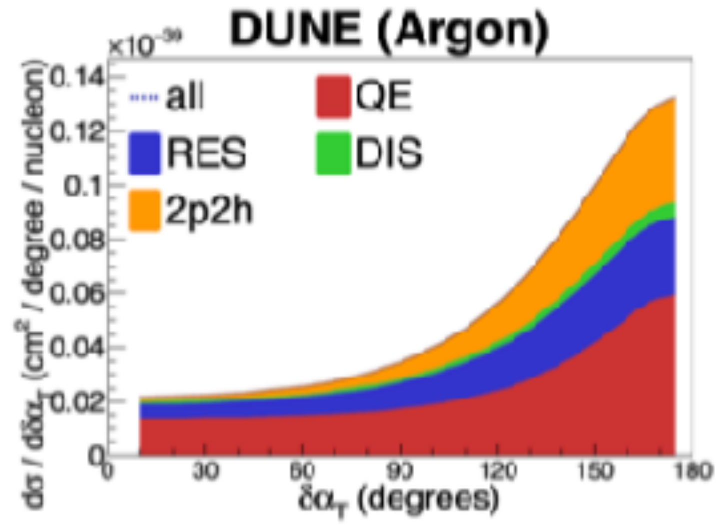
Learn more next week…

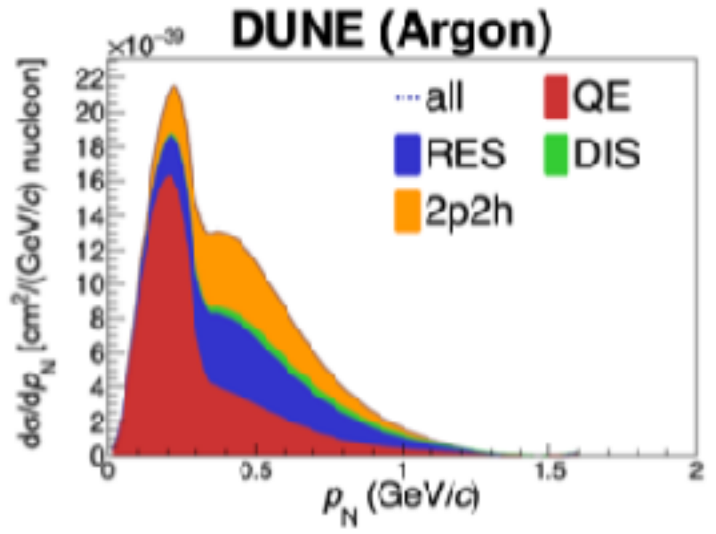




… how sensitive the detectors are to differences between interaction and nuclear models…

… and try for yourself in week 3!





…and how best to use them to study and untangle nuclear effects

Images and plots on this slide from arXiv:2103.13910 [physics.ins-det]

At the beginning I promised you'd learn…

Question 5

Why neutrino interactions are important

What we know about interactions

What we still need to understand better

How we're trying to understand them

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- Neutrinos are only detected when interacting
- Understanding interactions helps us reconstruct energy…
- … and identify modes that "fake" other interaction types

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- ν-nucleon - basic processes understood (QE, resonant, DIS…)
- nuclear models are best for small nuclei

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- Understand our sensitivity to models
- Test against data

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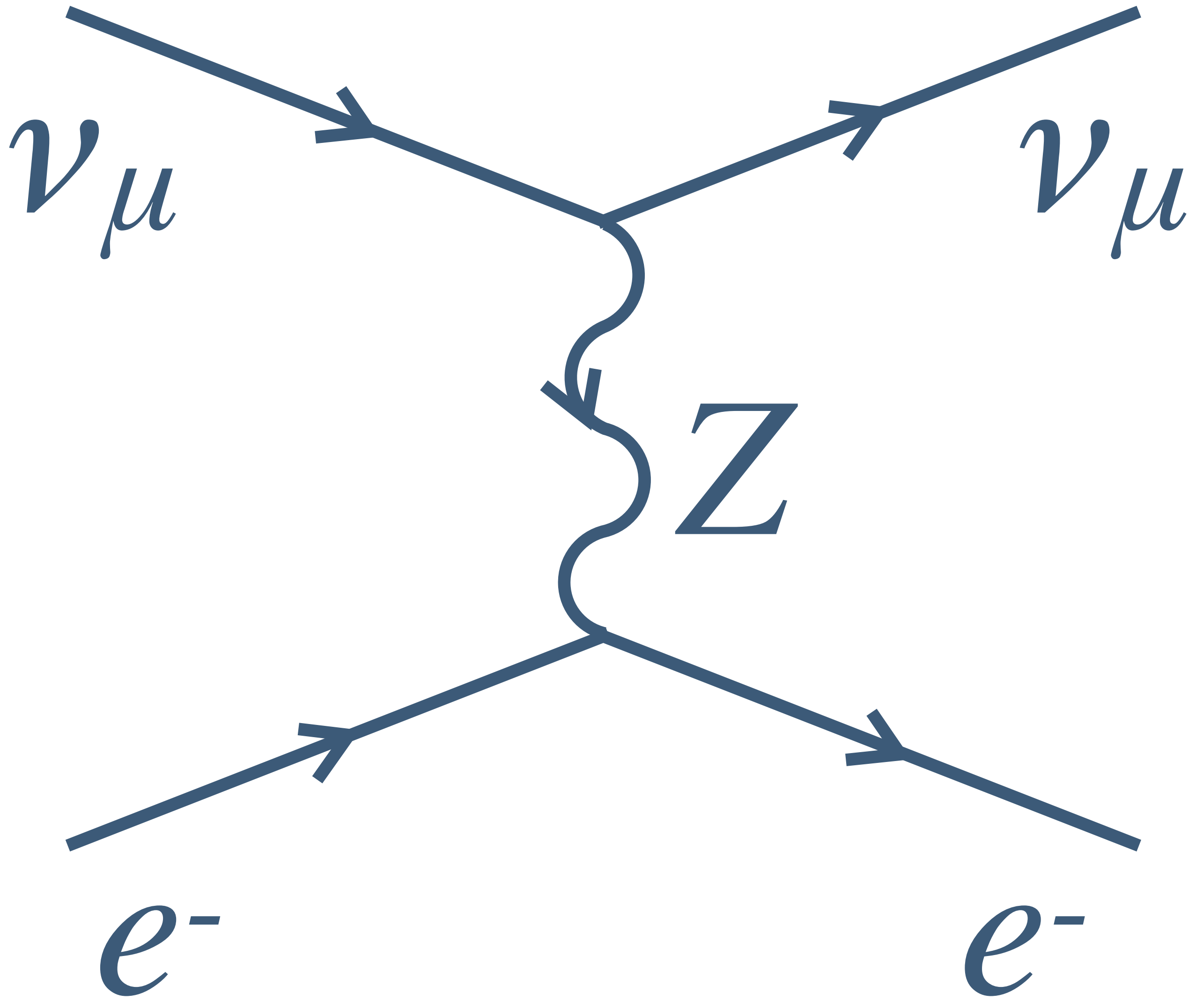
YOU CAN HELP!

Backup slides

Neutrino-electron elastic scattering



Squared center-of-mass energy

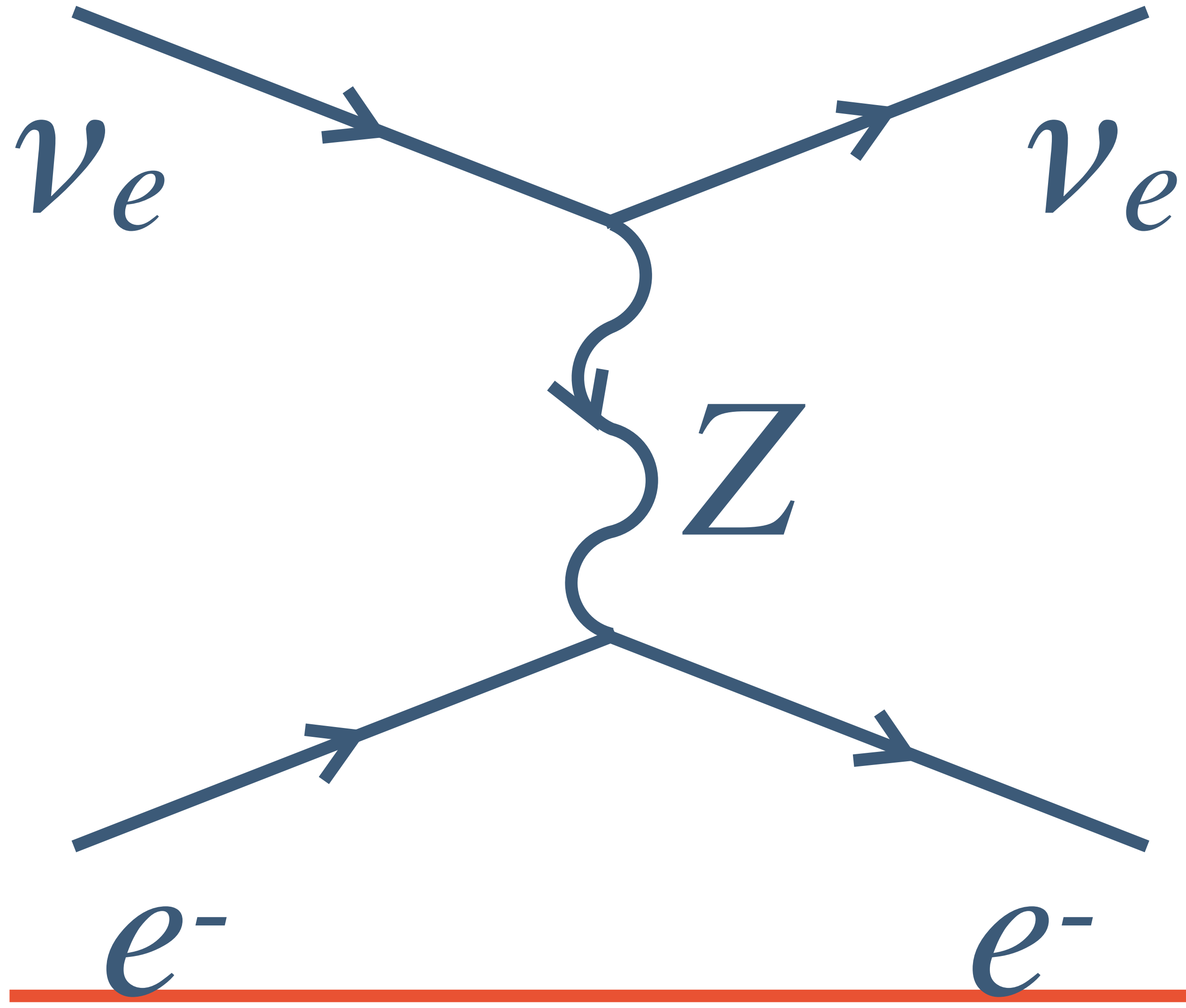
Inelasticity

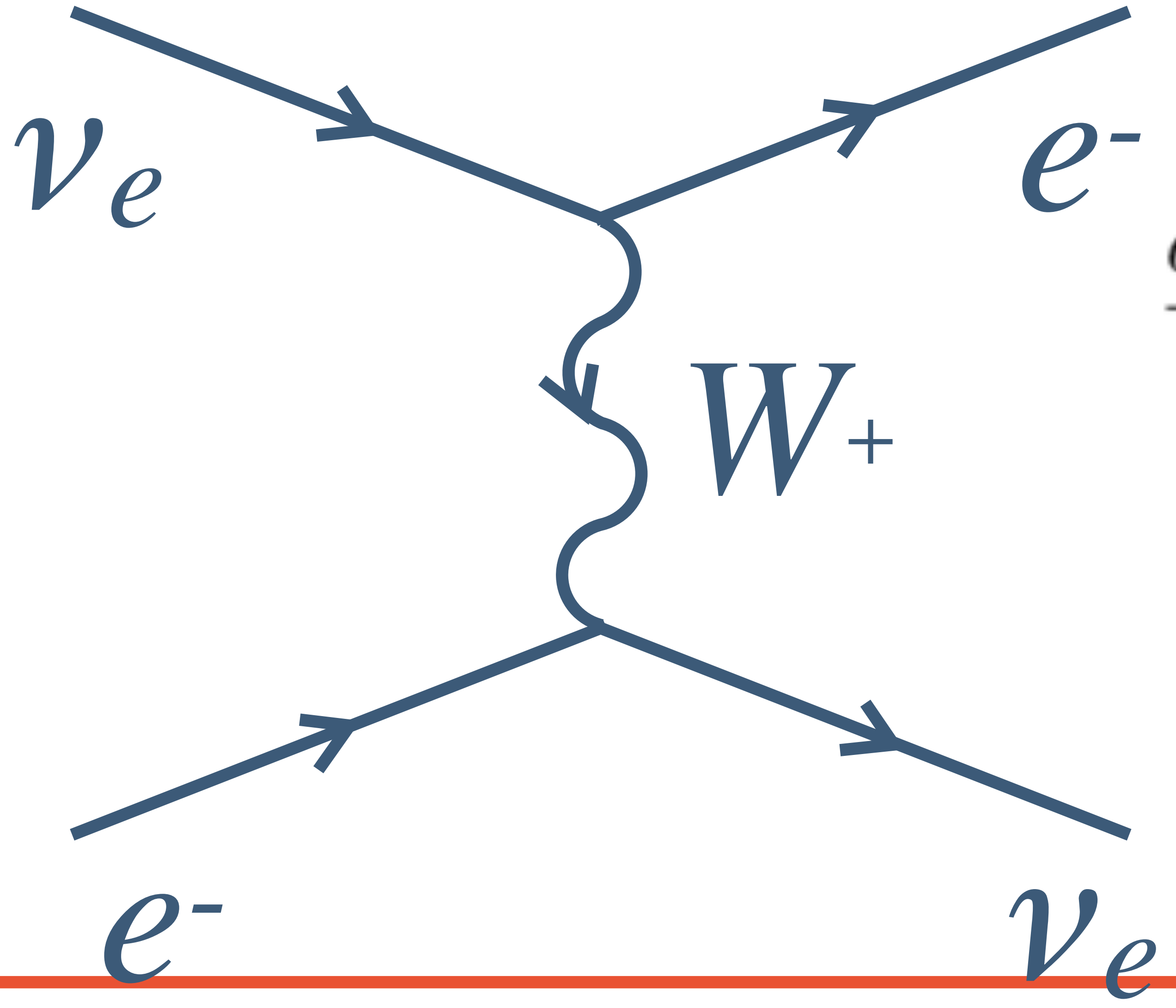
$$y = \frac{T_e}{E_\nu}$$

$$\frac{d\sigma(\nu e^- \to \nu e^-)}{dy} = \frac{G_F^2 s}{\pi}\left[C_{LL}^2 + C_{LR}^2(1-y)^2\right]$$

½ - $\sin^2\theta_W$

$\sin^2\theta_W$





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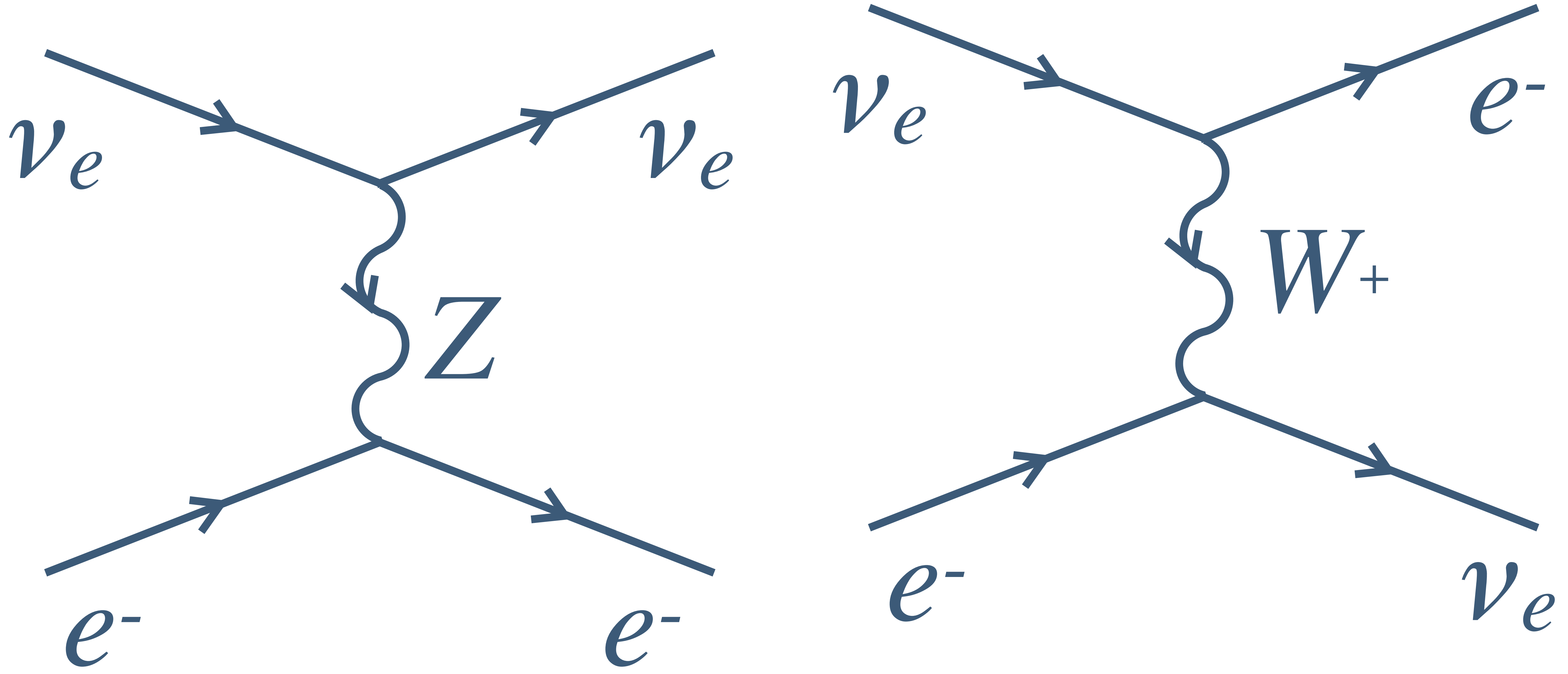
½ + $\sin^2\theta_W$

$\sin^2\theta_W$

Interference due to charged-current diagram

ν_e - electron scattering

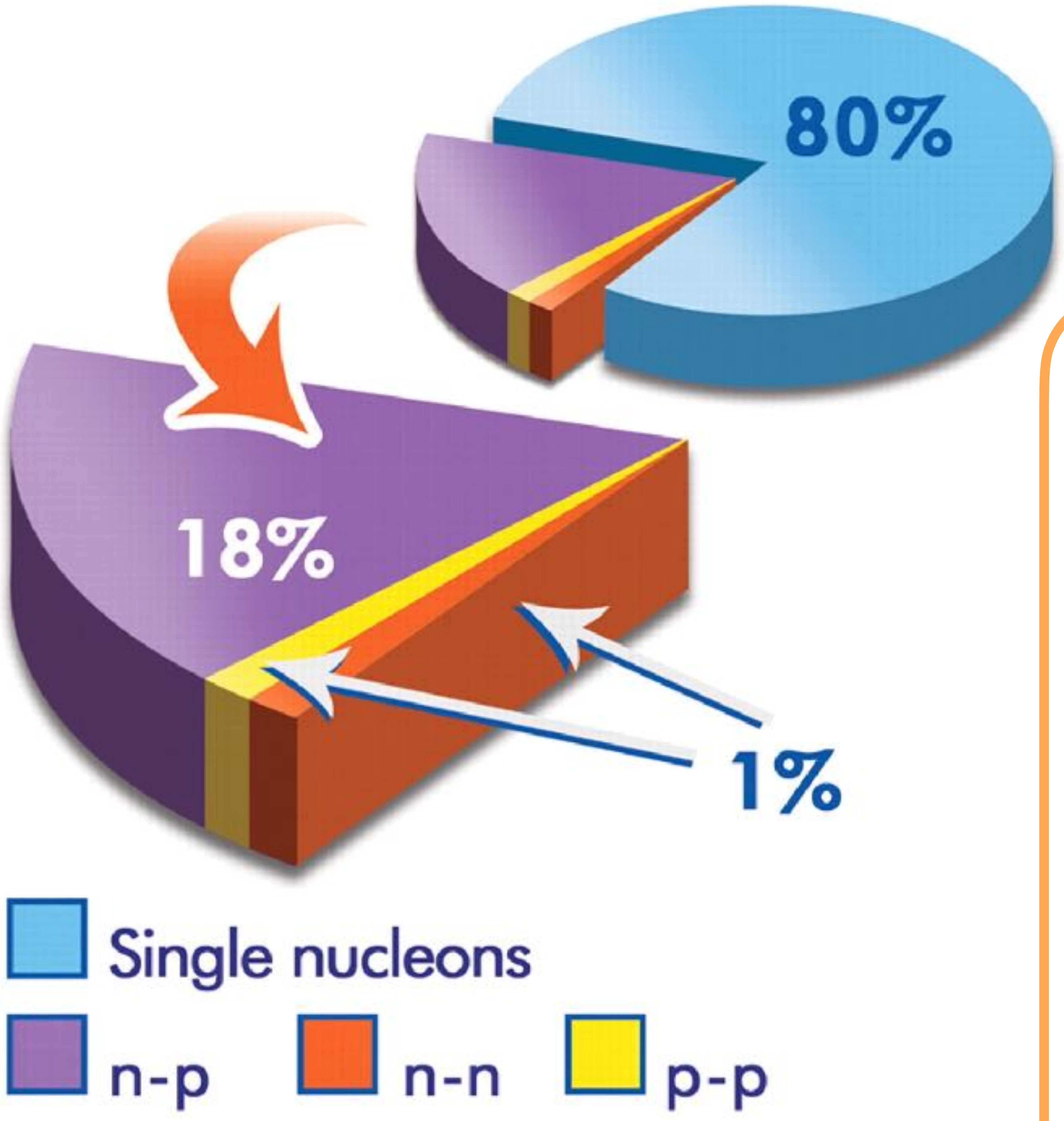


All lepton interactions have the same strengths in the weak interaction (lepton universality)

$$\frac{d\sigma(\nu e^- \to \nu e^-)}{dy} = \frac{G_F^2 s}{\pi}\left[C_{LL}^2 + C_{LR}^2(1-y)^2\right]$$

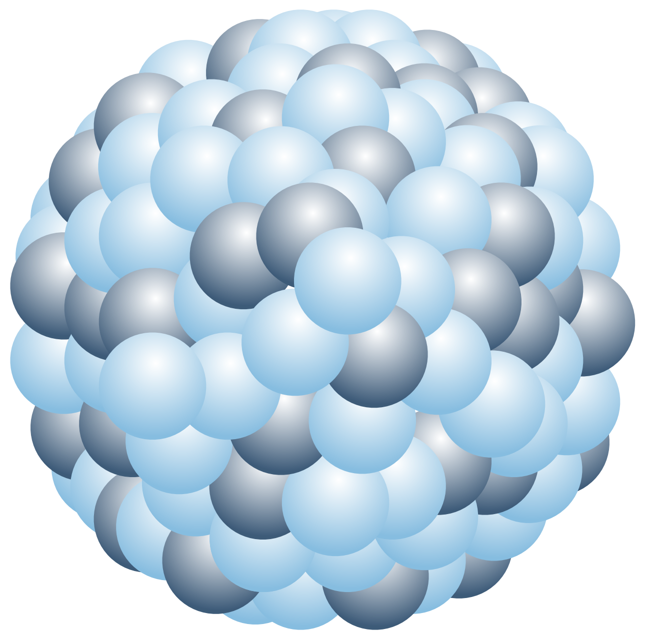
Interference due to charged-current diagram → ½ + $\sin^2\theta_W$ $\sin^2\theta_W$

SRC pairs in neutron-rich nuclei



This pie chart is for ^{12}C, which has 6 protons and 6 neutrons

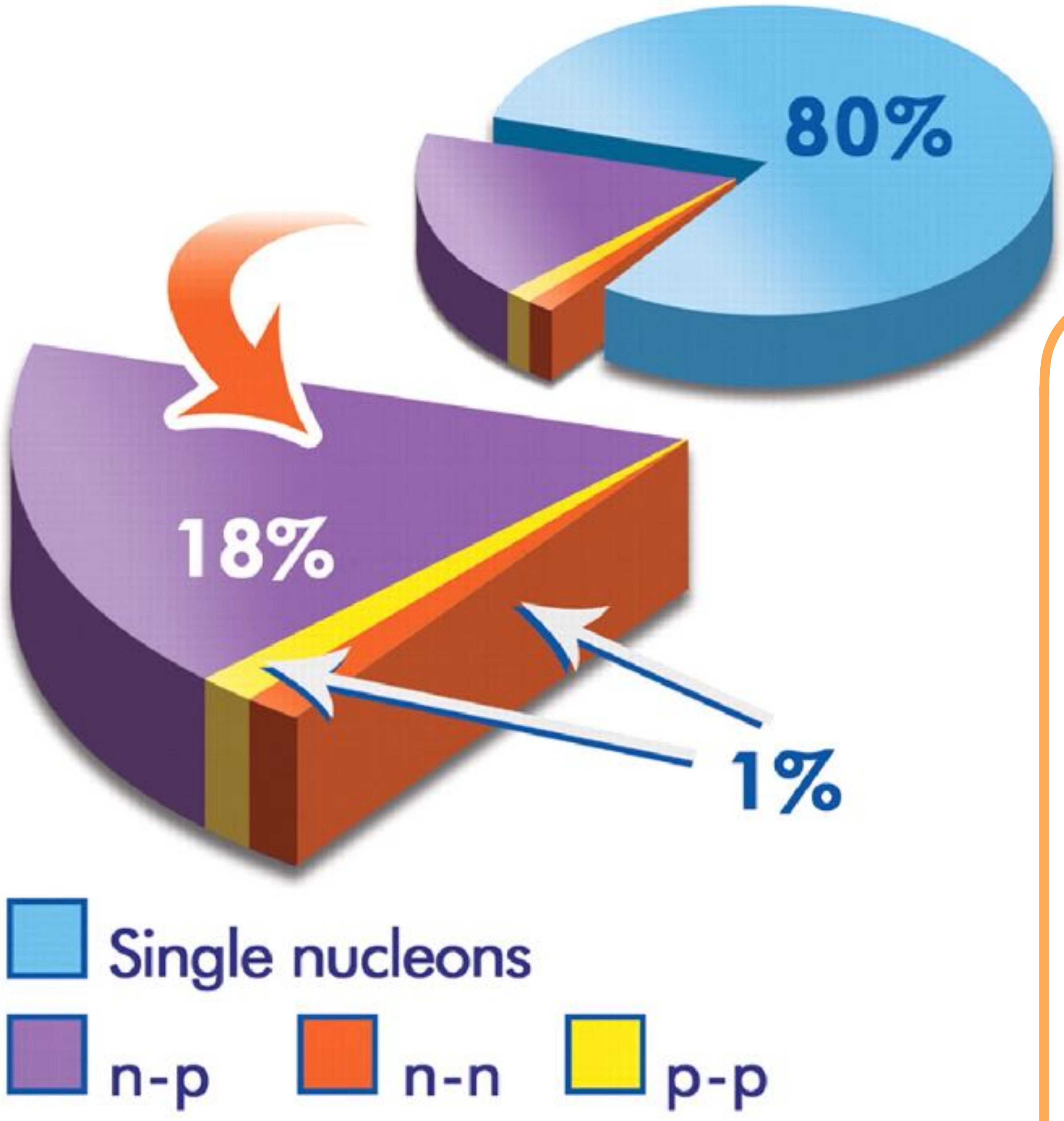
Lead-208 has



82 protons
and
126 neutrons

Are protons or neutrons more likely to be in correlated pairs, or is the probability the same?

SRC pairs in neutron-rich nuclei



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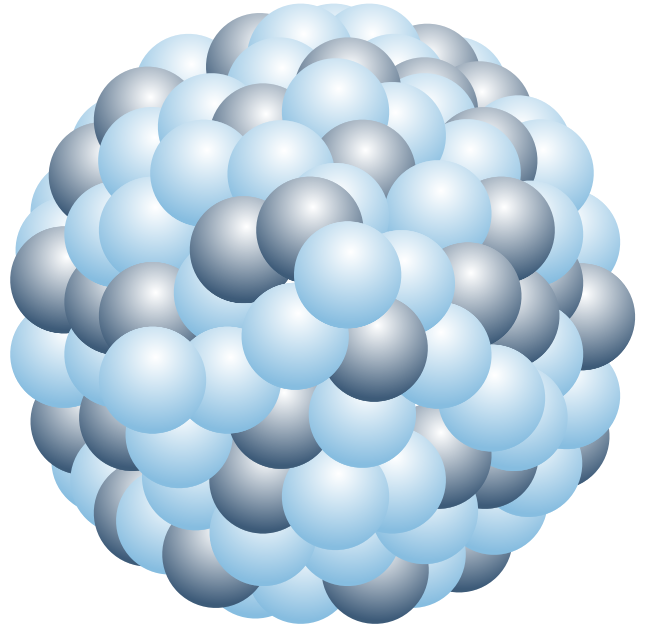

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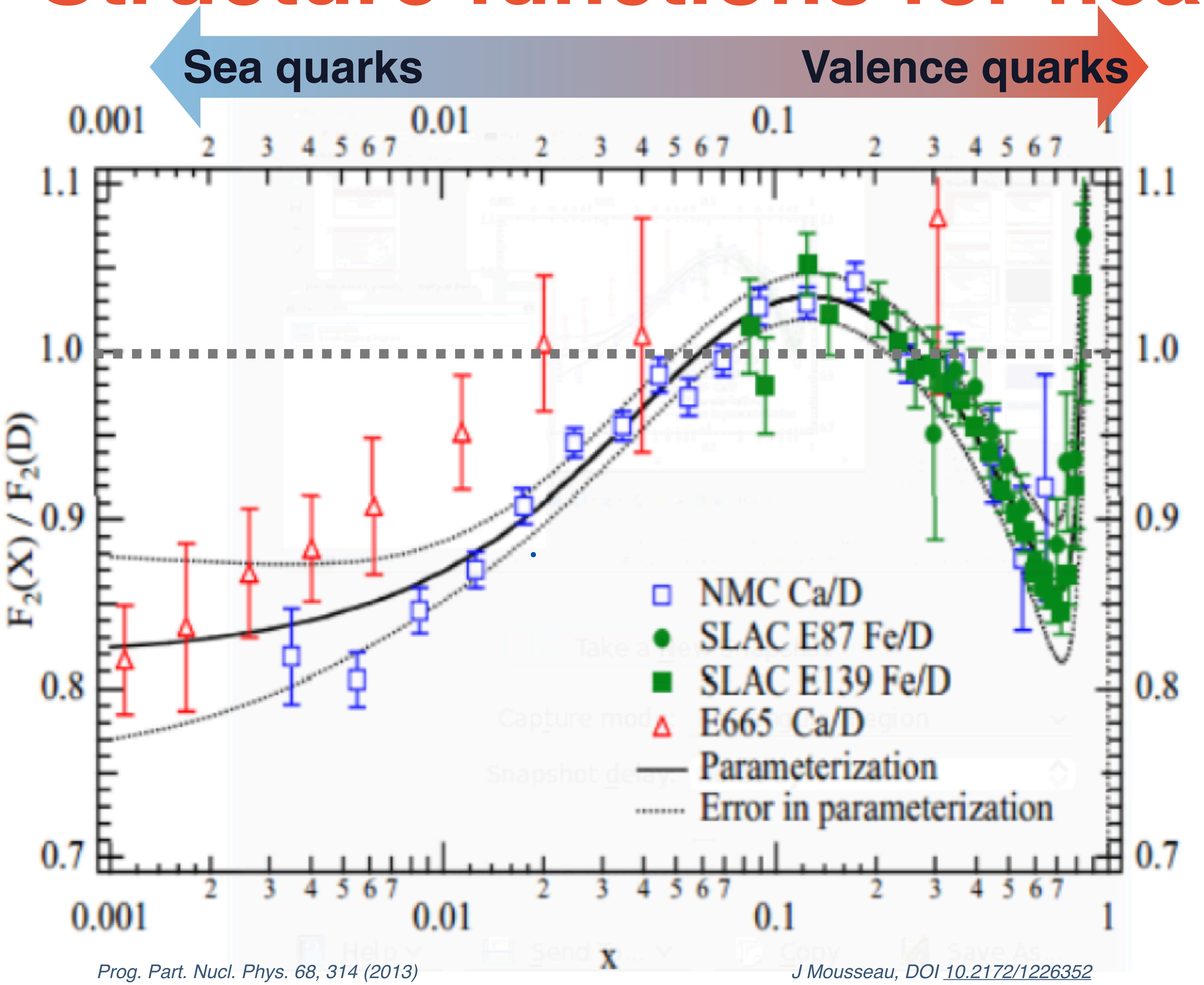
Are protons or neutrons more likely to be in correlated pairs, or is the probability the same?

In neutron-rich nuclei:

- Protons are more likely than neutrons to be in n-p pairs
- n-n pairs are more likely than p-p pairs

DUNE's detectors are made of $^{40}_{18}\mathrm{Ar}$. Why might we need to be careful of SRC when comparing scattering with ν_μ and $\bar{\nu}_\mu$?

Structure functions for heavy nuclei



Prog. Part. Nucl. Phys. 68, 314 (2013)

J Mousseau, DOI 10.2172/1226352

- Charged-lepton DIS from heavy nuclei ($^{40}_{20}$Ca and $^{56}_{26}$Fe)
- Ratio to scattering from deuterium ($^{2}_{1}$H)
- x separates **sea** and **valance** quarks

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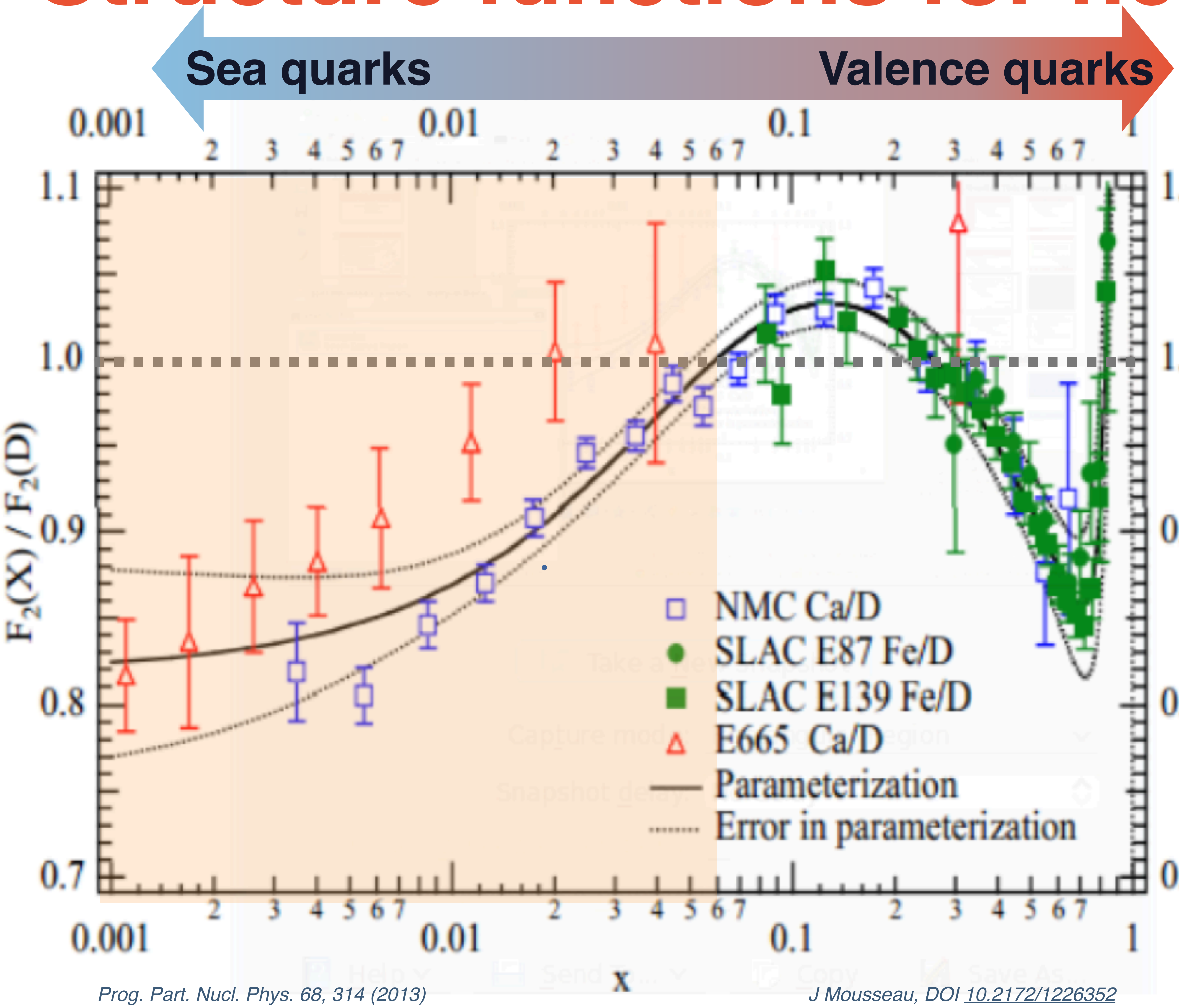

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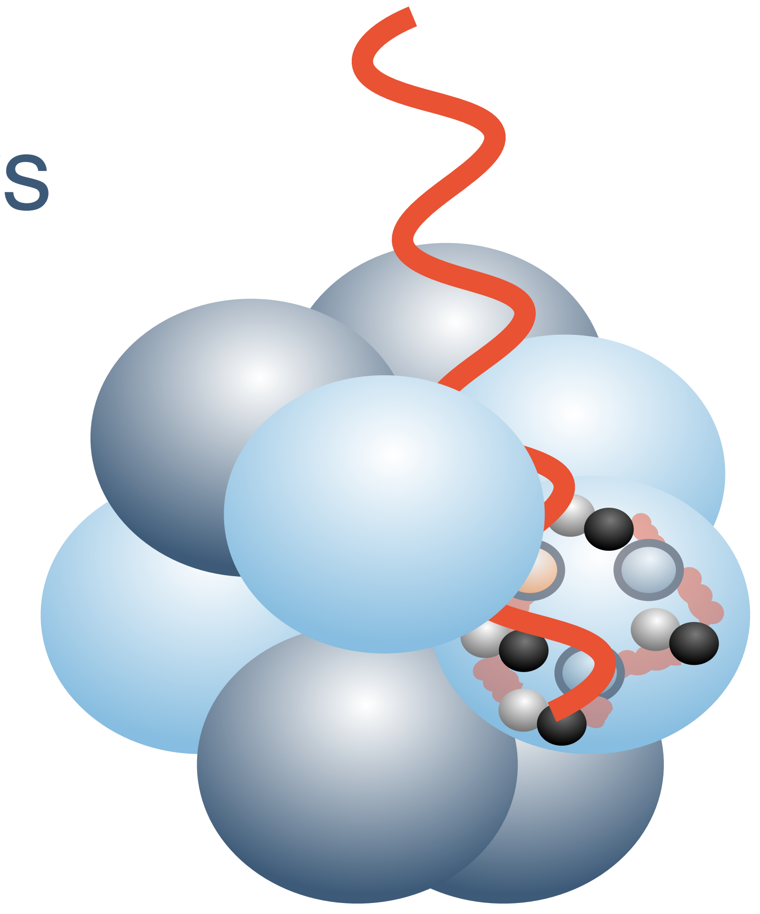
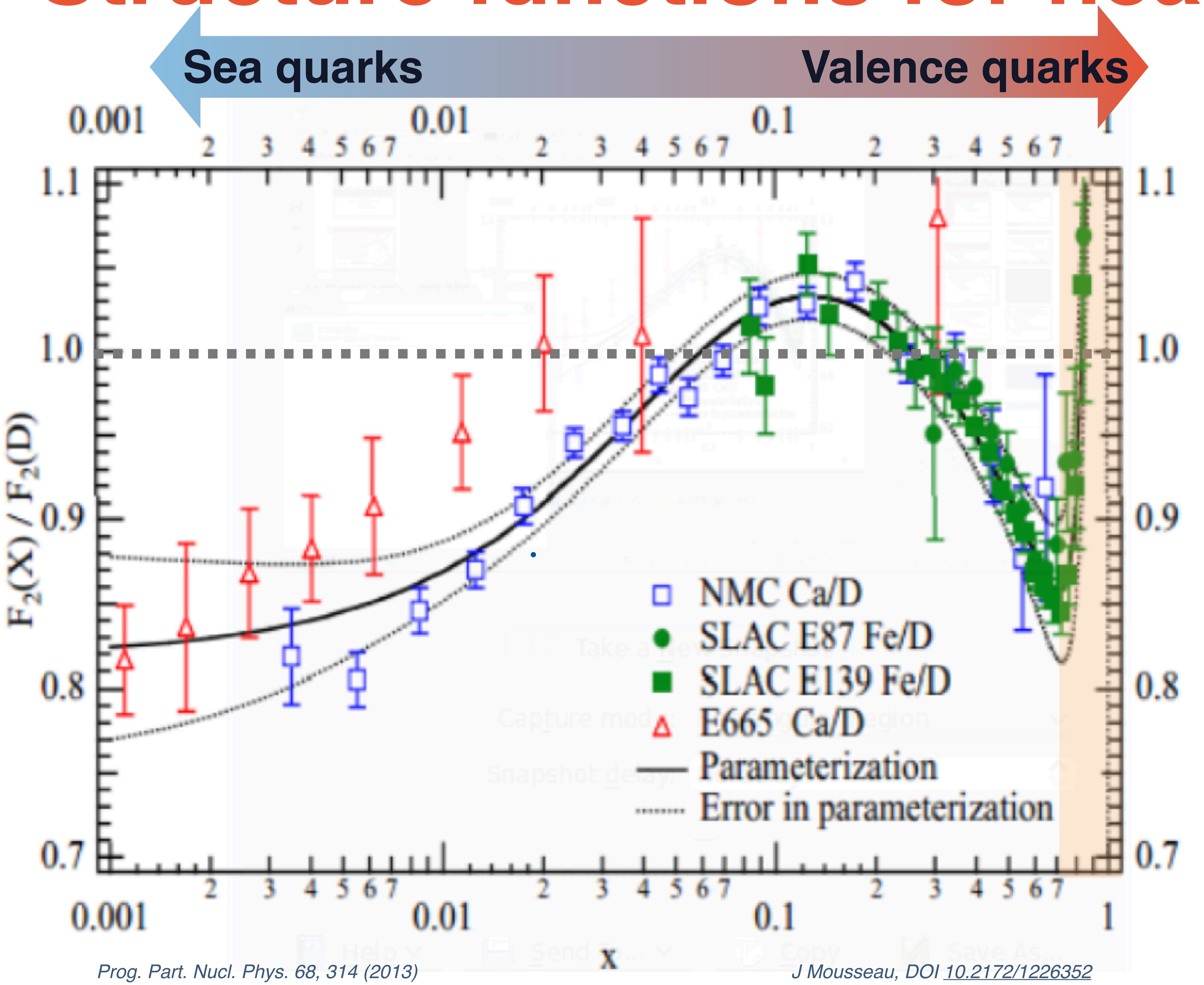
- x separates **sea** and **valance** quarks

Shadowing: $x \lesssim 0.1$: the interacting W (or Z) is shielded by other nucleons in the nucleus, reducing the cross section

Shadowing is different for neutrinos vs electrons, sea vs valence quarks, and is important at low Q^2



Structure functions for heavy nuclei



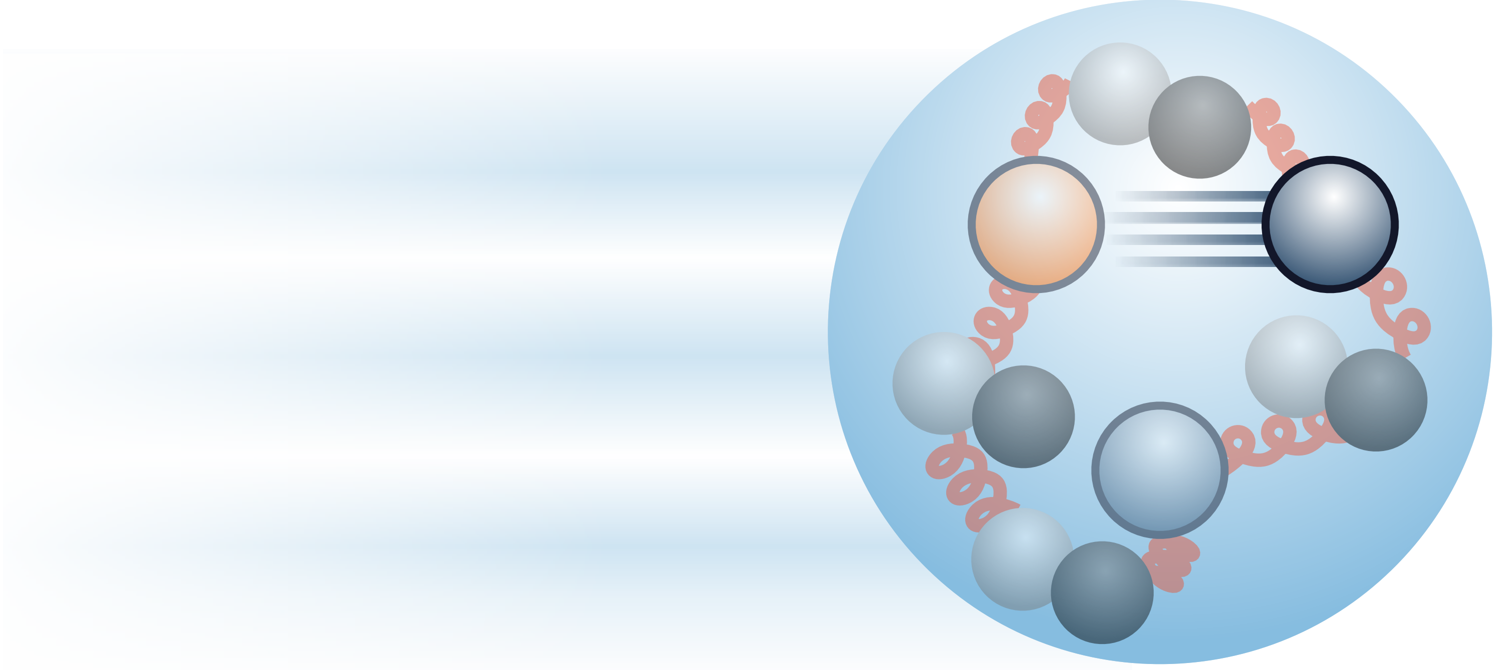
Prog. Part. Nucl. Phys. 68, 314 (2013)

J Mousseau, DOI 10.2172/1226352

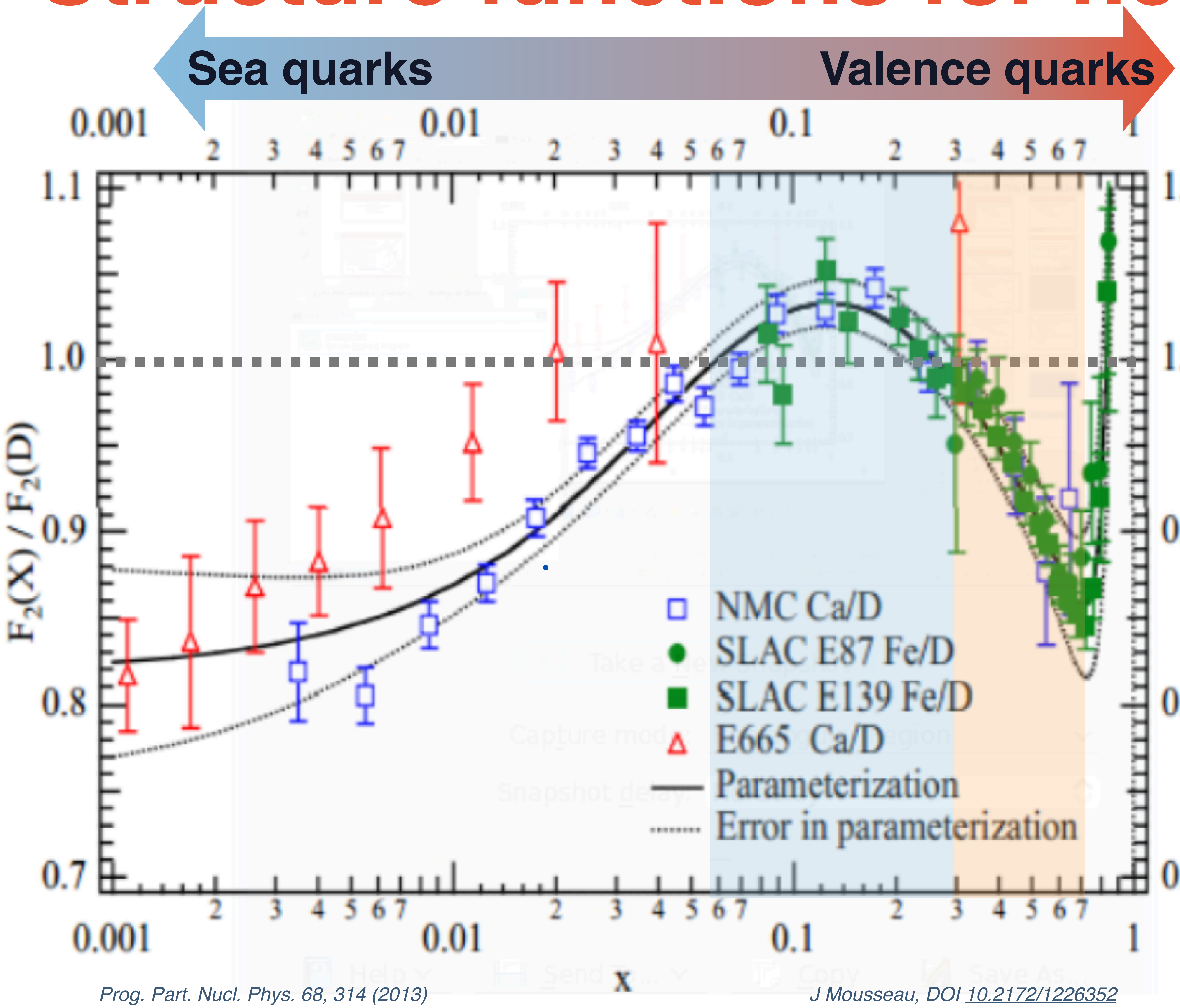
- Charged-lepton DIS from heavy nuclei ($^{40}_{20}$Ca and $^{56}_{26}$Fe)
- Ratio to scattering from deuterium ($^{2}_{1}$H)
- x separates sea and **valance** quarks

Shadowing: $x \lesssim 0.1$: the interacting W (or Z) is shielded by other nucleons in the nucleus, reducing the cross section

Fermi motion: $x \gtrsim 0.7$: nucleons in nuclei are moving, so can boost a quark's momentum



Structure functions for heavy nuclei



Sea quarks

Valence quarks

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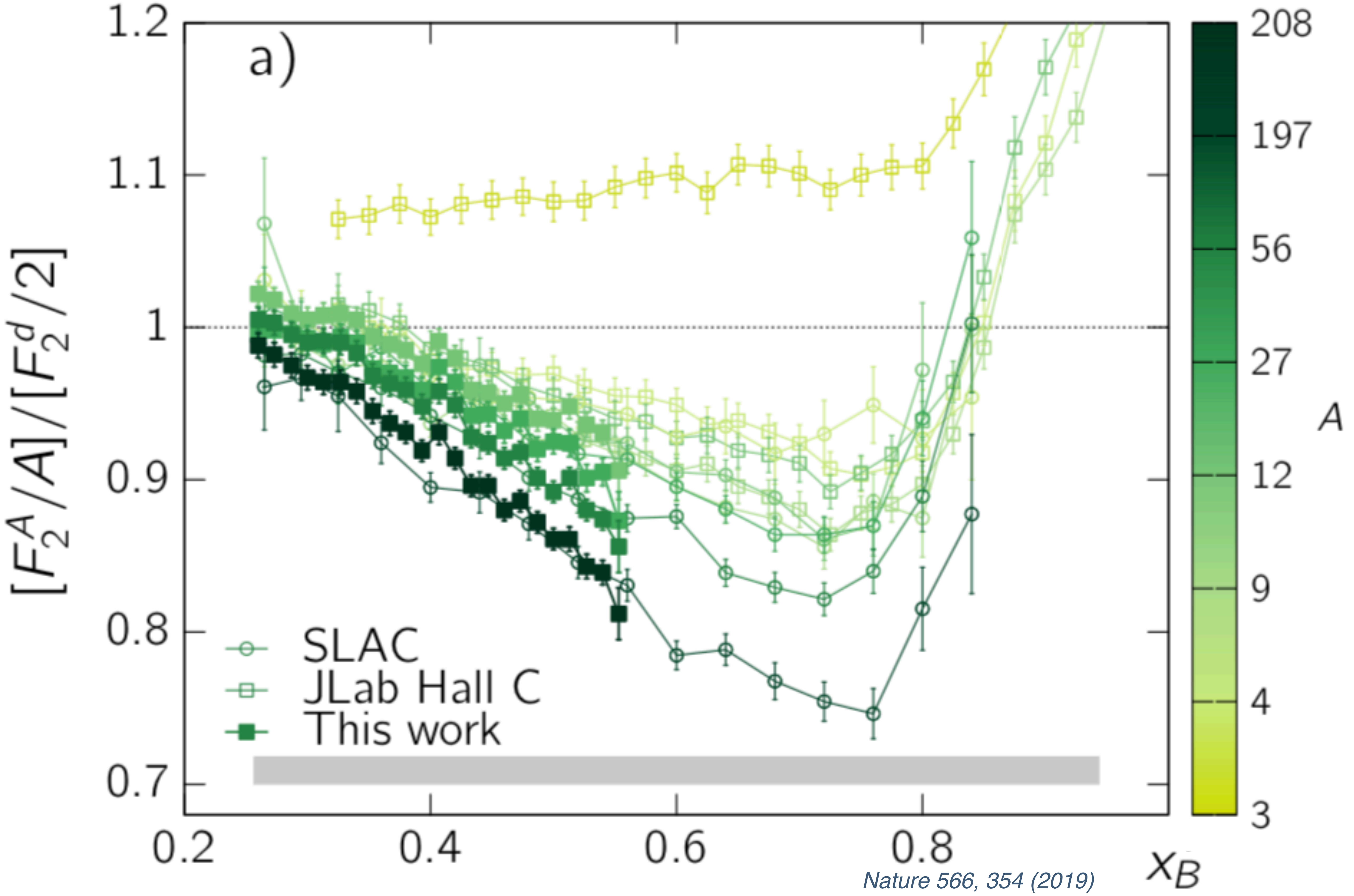
The **EMC effect** and **anti-shadowing** enhancement are poorly understood but may be due to nucleon-nucleon pairs - more on this soon!

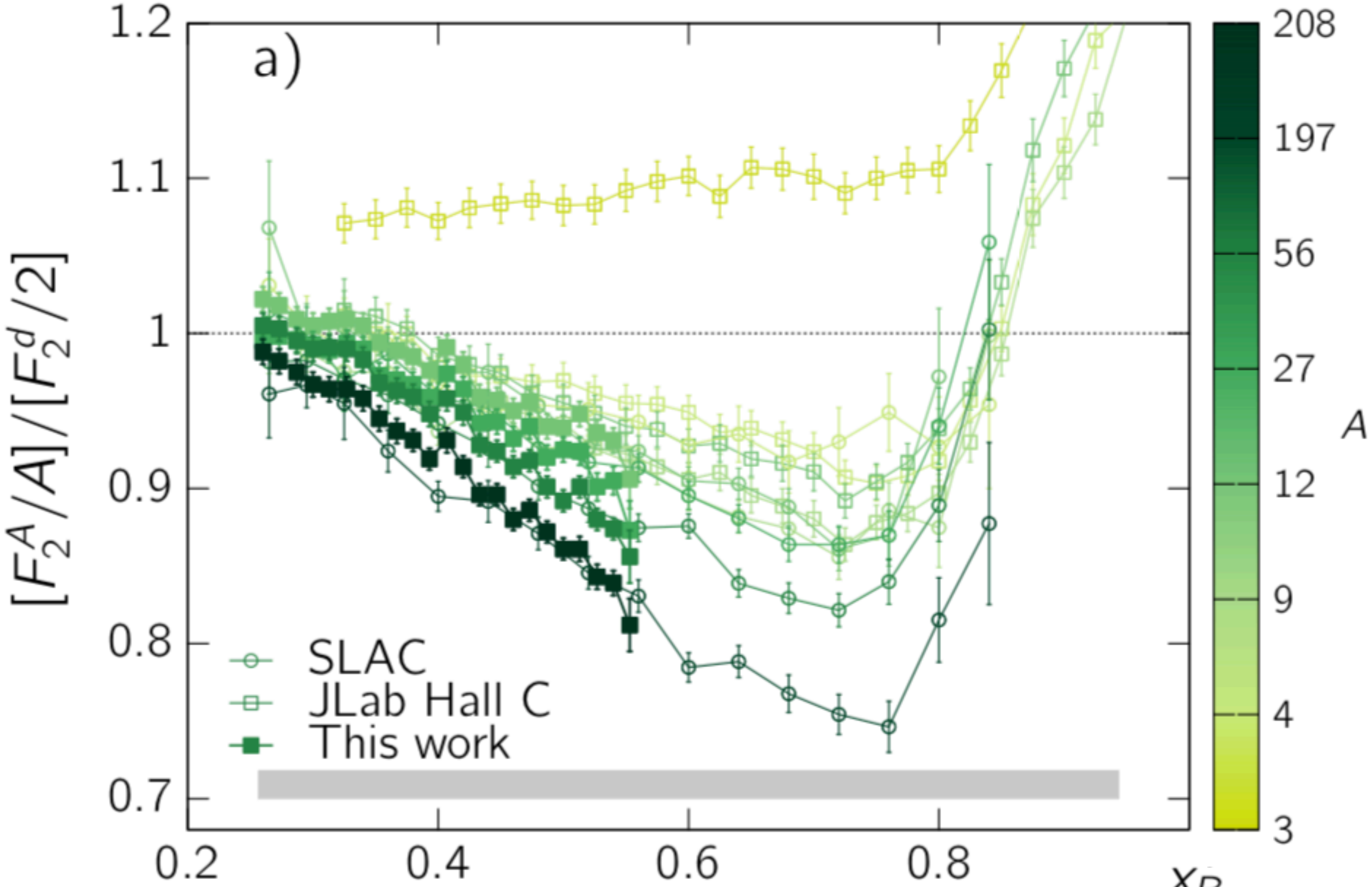
Short-range correlations and the EMC effect



Nature 566, 354 (2019)

The EMC effect for different nuclei
(structure function ratio to deuterium)

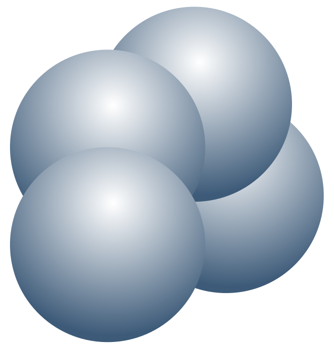
Short-range correlations and the EMC effect



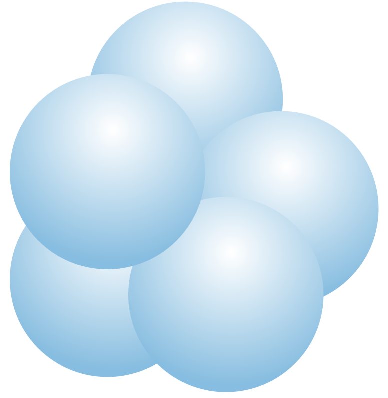
Nature 566, 354 (2019)

The EMC effect for different nuclei
(structure function ratio to deuterium)

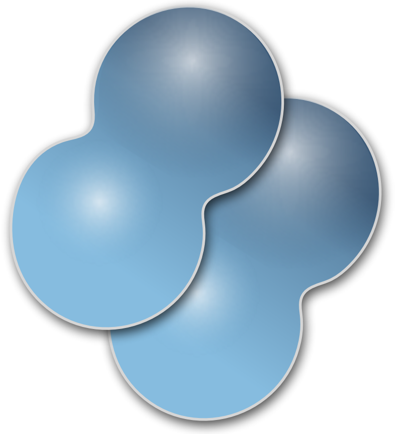
Divide the structure function F_2^A into:



A proton part F_2^p times the number of protons



A neutron part F_2^n times the number of neutrons



An SRC part $\Delta F_2^p + \Delta F_2^n$ times the number of SRC pairs

Short-range correlations and the EMC effect

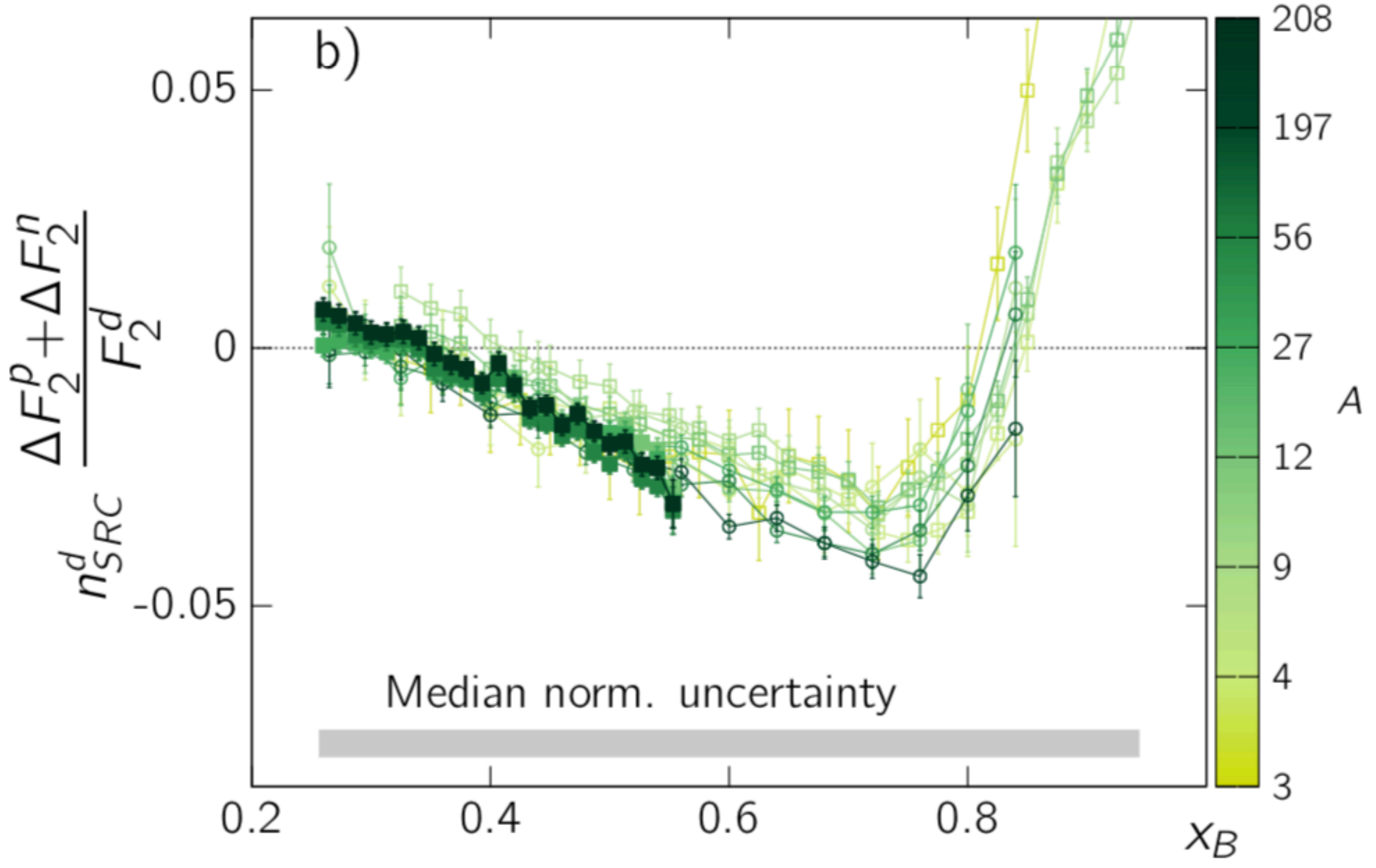
Nature 566, 354 (2019)

The EMC effect for different nuclei (structure function ratio to deuterium)

The SRC part, if scaled by the number of n-p pairs, is the **same for all nuclei**! This **universality** suggests SRC pairs are key to the EMC effect

Empirical models and scaling techniques

This EMC plot showed a **universal** property - the **same for many nuclei**



Empirical models and scaling techniques

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Can we find a **super-scaling** model? That means

$$\frac{\sigma(q,w)_{\text{nucleus}}}{\sigma(q,w)_{\text{nucleon}}}$$

- is a function of a **single variable** (some complicated function of q, W…)
- has the same form for **all nuclei**

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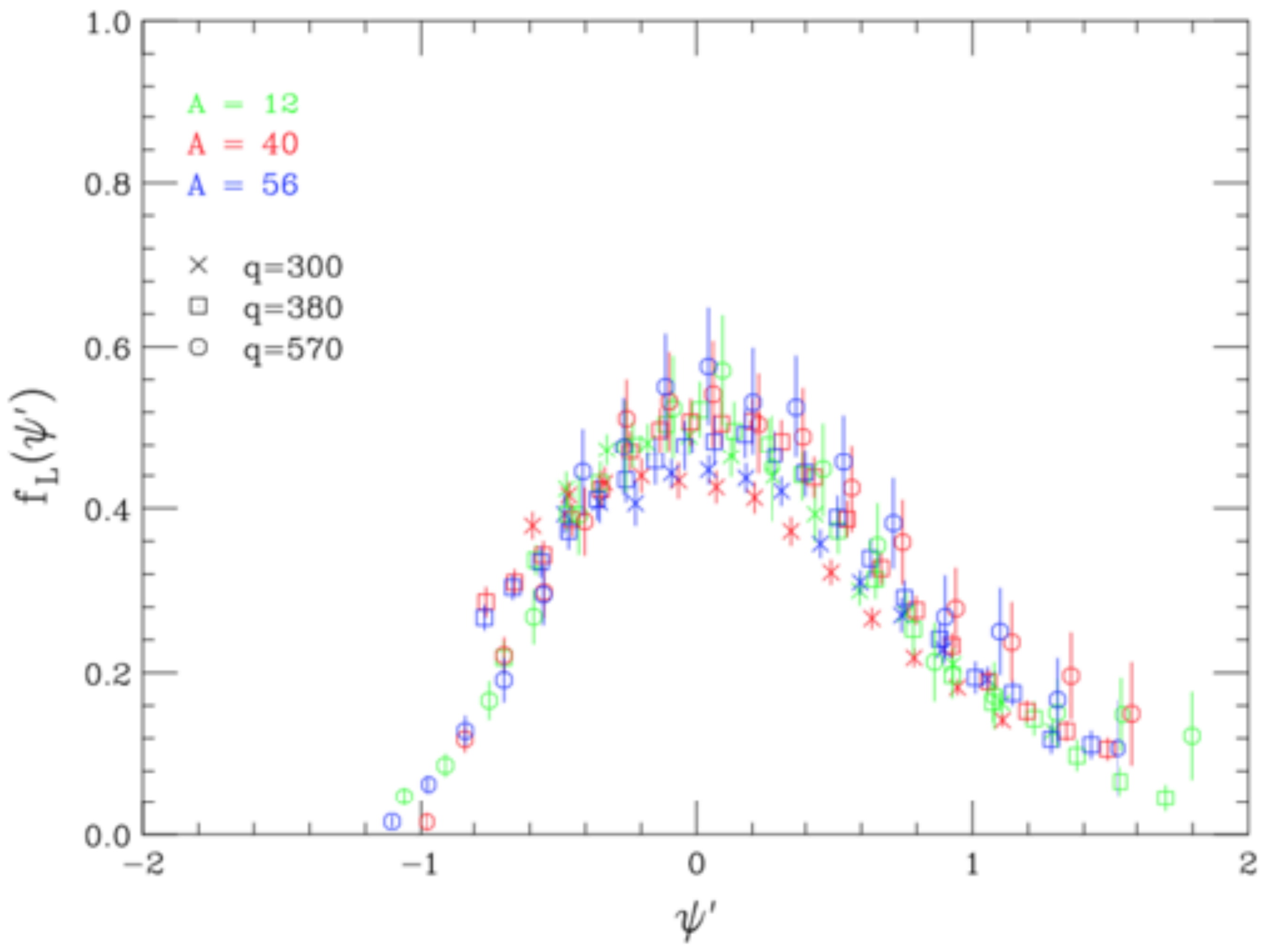
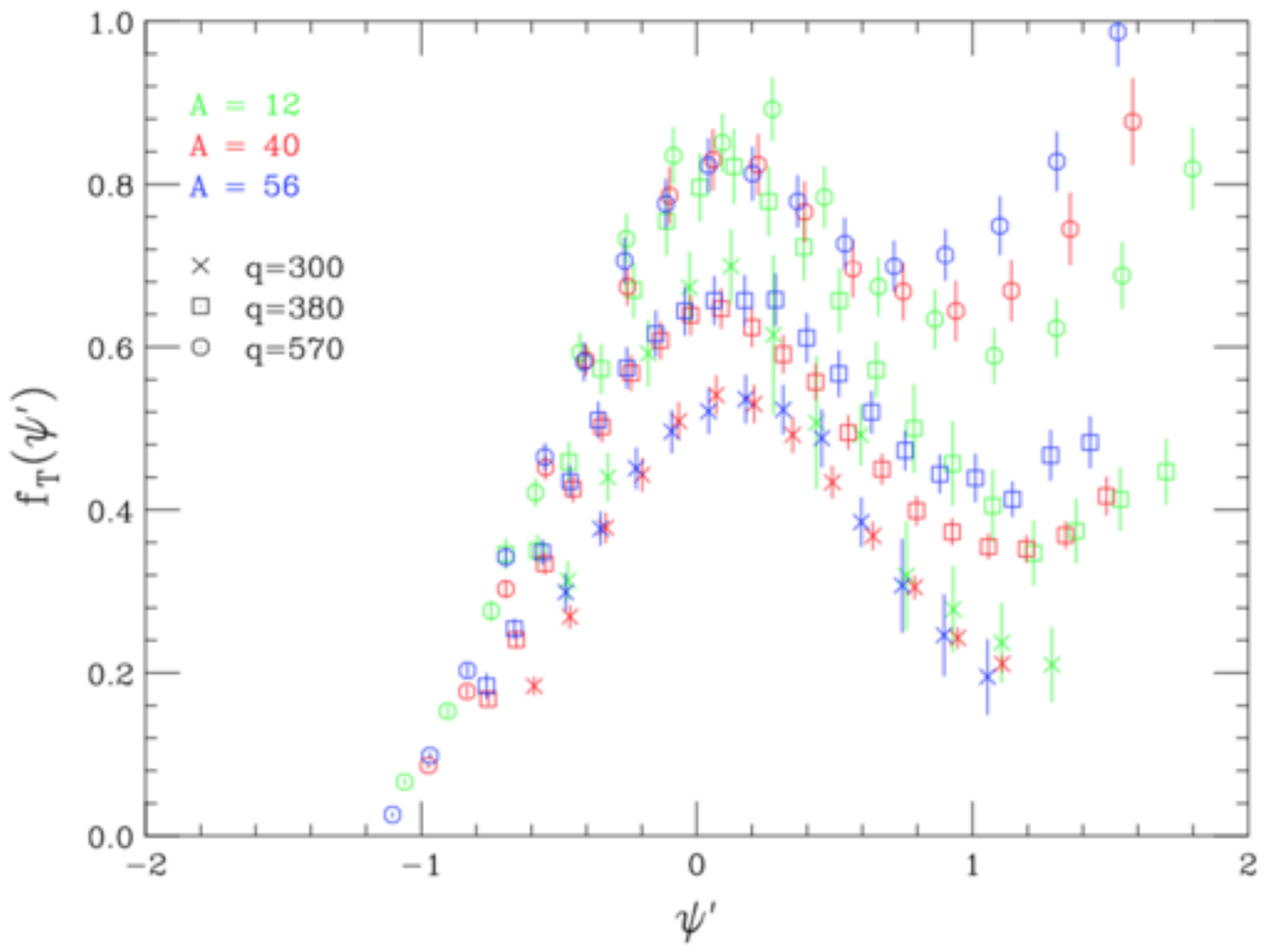
Some **super-scaling variables** work well for electron scattering in some regimes… can these models be extended?

Phys. Rev. C, 71:015501, Jan 2005.



This scaling function agrees well for different nuclei (colors) and momentum transfers (shapes), if the exchanged photon is **longitudinally** polarized…



…but poorly if it is transversely polarized, due to multi-nucleon effects

Phys.Rev. C60 (1999) 065502